Modern theory of plasma-cathode interaction in high-pressure arc discharges and perspectives of its application to cathode spots in vacuum arcs

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***Abstract*- Understanding of cathode phenomena in high-pressure arc discharges has considerably improved during the last decade due to effort invested by researchers from several countries. This talk is concerned with a review of present understanding of cathodes of high-pressure arcs, with an emphasis on theoretical and modeling aspects and on perspectives of transfer of the results to vacuum arcs.**

I. Introduction

Cathodes of high-pressure arc discharges have been under intensive investigation for many decades; a review published in 1961 by Ecker [1] already included more than 600 references. However, reliable experimental data and self-consistent theoretical models started to emerge only in the 1990s. By now, the theory of plasma-cathode interaction in high-pressure arc discharges is developed relatively well; see review [2].

Results achieved in the theory of high-pressure arc cathodes, apart from being of scientific and technological importance by itself, are of interest due to their potential importance for understanding operation of cathodes of vacuum arc discharges, which is still incomplete in spite of many decades of intensive investigation. Depending upon the electron emission and metal vapor generation processes, models of cathode spots in vacuum arcs can be divided into two categories, evaporation models and explosive models. In the framework of evaporation models, the physics of cathode spots in vacuum arcs is not fundamentally different from the physics of cathode spots in high-pressure arc discharges. Therefore, understanding of cathode phenomena in vacuum arcs may considerably benefit from results achieved recently on cathode phenomena in high-pressure arcs.

This talk is concerned with a review of present understanding of cathodes of high-pressure arcs, with an emphasis on theoretical and modeling aspects, and of perspectives of transfer of the results to vacuum arcs. The model of nonlinear surface heating, on which the theory is based, is presented and discussed, along with its numerical realization. Modeling results are given for axially symmetric cathodes. The steady-state modes presented and discussed include the diffuse mode and different spot modes. A good agreement between the

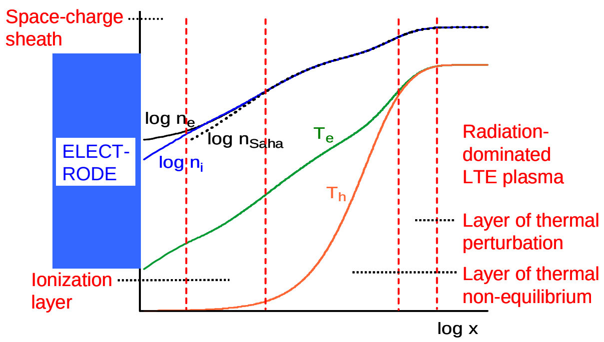

Fig. 1. Structure of the near-electrode perturbation region in high-pressure arc discharges.

modeling results and results of electrical and thermal measurements is demonstrated. Results of analytical and numerical investigation of stability of different modes of current transfer are presented and discussed. Other topics include theoretical and experimental investigations of transient regimes of current transfer; modeling of multi-species plasmas with complex chemical kinetics; effect of variation of the work function of the cathode surface; theory of solitary spots, i.e., spots on large cathodes (the spot radius is determined in a self-consistent way). A free online tool for simulation of axially symmetric modes of current transfer is demonstrated. The possibility to apply the results to cathode spots in vacuum arcs is discussed in detail.

II. Theory of Plasma-Cathode Interaction

A. Structure of the Near-Cathode Perturbation Region

Different kinds of perturbations introduced into the arc plasma by electrodes manifest itself on different length scales. This allows one to divide the near-electrode perturbation region into a number of sub-regions with different physics as shown in Fig. 1. Two of these sub-regions are particularly important as far as the cathode phenomena are concerned: the ionization layer and the space-charge sheath. The ion flux to the cathode surface is generated in the ionization layer. The ions, after having been accelerated by the sheath electric field, bring their energy to the cathode surface. This is the main mechanism of heating of the cathode, although some additional heating may be

Work on this paper was supported by the projects PPCDT/FIS/60526/2004 *Modes of current transfer to cathodes of high-pressure arc discharges and their stability* of FCT, POCI 2010 and FEDER and *Centro de Ciências Matemáticas* of FCT, POCTI-219 and FEDER.

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provided by fast plasma electrons that can overcome the decelerating electric field in the sheath and reach the cathode surface. Energy necessary for ionization in the ionization layer comes from acceleration by the sheath electric field of electrons emitted by the cathode.

In the following, the ionization layer and the space-charge sheath jointly will be termed the near-cathode layer. The near-cathode layer gives a dominating contribution to the voltage drop in the whole near-cathode perturbation region. It follows that the voltage drop U in the near-cathode layer is approximately the same for all points of the arc attachment.

B. The model of Nonlinear Surface Heating

The above means that the plasma-cathode interaction in high-pressure arc discharges is governed by a thin near-cathode plasma layer comprising the space-charge sheath and the ionization layer, and this near-cathode plasma layer is to a first approximation unaffected by the outside plasma. Therefore, there is in principle no need to calculate the whole system arc-cathode simultaneously: one can first find a solution for the near-cathode layer, then a solution describing the cathode, and finally a solution for the arc column. More specifically, the procedure is as follows.

As a first step, one calculates characteristics of the near-cathode layer. Since this layer is much thinner than a characteristic dimension of the arc attachment, it may be treated as locally one-dimensional (1D). Therefore, characteristics of the near-cathode layer are found as functions of the local surface temperature T_w and the near-cathode voltage drop U. (It should be stressed that in the framework of such approach current transfer across the near-cathode layer to any point of the arc attachment depends only on the temperature of the cathode surface at this point but not at other points; the near-cathode voltage drop U represents a combined voltage drop in the space-charge sheath and in the ionization layer and is the same for all points of the arc attachment.) In particular, densities of the net energy flux and the electric current from the plasma to the cathode surface are found: $q=q(T_w,U)$, $j=j(T_w,U)$. These characteristics do not depend on the total arc current or the shape of the cathode and it is sufficient to calculate them only once for every given combination of the cathode material, the plasma gas and its pressure.

At the second step, one calculates the temperature distribution inside the cathode body and on the surface. This amounts to solving inside the cathode the (multidimensional) heat conduction and current continuity equations with the boundary conditions supplied by the dependences $q=q(T_w,U)$ and $j=j(T_w,U)$. If the Joule heat production in the body of the cathode is unessential, which is usually the case for low-current high-pressure arcs, the current continuity equation may be excluded from consideration. After this problem has been solved, one can substitute the surface temperature distribution obtained as a part of the solution into the dependences found at the previous step, thus determining distributions of parameters of the near-cathode layer along the cathode surface. Integrating the current density distribution, one finds the arc current corresponding to the considered value of the near-cathode voltage U.

If the principal aim of a study consists in a modeling of a cathodic part of the discharge, which is the case, e.g., in investigations dealing with cathode erosion, the procedure of solution terminates here. Otherwise, one can calculate the arc plasma outside the near-cathode layer, taking necessary boundary conditions from the solution obtained at the second step; the third step.

The above-described approach is usually referred to as the model of non-linear surface heating. The most important features of this model are as follows. First, the models is self-consistent: what is specified is not a distribution of the energy flux from the plasma over the surface but rather a dependence of the energy flux density on the local surface temperature, this temperature being unknown *apriori*. Second, the model admits under certain conditions more than one solution at the same value of the arc current, with different solutions describing different modes of current transfer. This feature allows for a self-consistent calculation of different modes, thus eliminating the necessity of switching different mechanisms (such as thermionic electron emission versus thermo-field or field emission) "by hand" in order to calculate different modes, which is a usual way of simulating different modes in other models.

The model of nonlinear surface heating was apparently first suggested in 1963 by Bade and Yos [3], who not only gave a mathematical formulation of the problem but also forwarded an assumption of existence of two or more solutions for any given set of input conditions, corresponding to different modes of cathode operation. However, neither such multiple solutions were found in [3] nor their existence was proved, and the importance of this work has not been properly appreciated at the time. As a consequence, the model of nonlinear surface heating was virtually forgotten for several decades and has apparently been re-discovered, with some or other variations, more than once. A revival of the model of nonlinear surface heating has started in the 1990s, after it was proved that the model indeed gives multiple solutions describing different modes of current transfer. It is interesting to note that the first such proof [4] was given by means of the bifurcation analysis, which is a usual tool in studies of self-organization in nonlinear dissipative systems. Understanding of the fact that different modes of current transfer to cathodes of high-pressure arc discharges represent self-organization phenomena and must be described as such was beneficial also for the subsequent development of the theory. By now, the model of nonlinear surface heating has become virtually universally accepted.

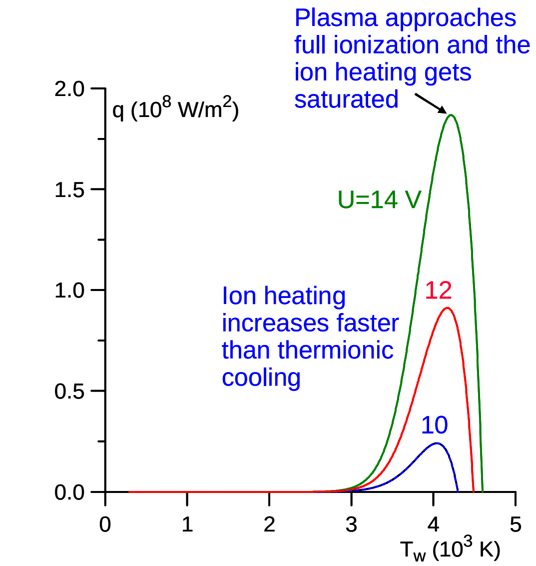

Fig. 2. Density of the net energy flux from a high-pressure arc to the cathode surface vs. the local surface temperature. W cathode, Ar plasma, *p*=1bar.

III. Examples of Modeling Results

A. Solution on the Plasma Side

An example of the dependence $q(T_w,U)$ can be seen in Fig. 2 (calculations by means of the model [5]–[7]). A detailed discussion of this dependence can be found in [6]; here we only note the following. The dominating mechanisms of energy exchange between the plasma and the cathode at these values of U are the ion heating and cooling by thermionic emission. At relatively low T_w the ion heating grows with increase of T_w faster than thermionic cooling, so the net energy flux to the cathode surface increases. As T_w increases and the ionization degree on the plasma side of the ionization layer approaches unity, the increase of the ion current slows down; the increase of thermionic cooling overcomes increase of ion heating and the net energy flux starts to decrease. Note that the dependence of q on T_w in the case of higher U possesses two maxima. The first maximum originates in a deviation of the ion current to the cathode surface from the diffusion value; the second maximum is due to a rapid increase of the heating by plasma electrons which is subsequently overcome by thermionic cooling.

The non-monotony of the dependence of q on T_w, which is seen in Fig. 2, is the root reason of existence of multiple modes of current transfer to thermionic cathodes. The growing section of this dependence, which occurs at relatively low T_w around 3000K, is potentially unstable: a local increase of the surface temperature will result in an increase of the local energy flux from the plasma; the latter will cause a new increase of the local temperature etc, i.e., a thermal instability may develop. Note that a growing dependence $q(T_w)$ is unusual from the point of view of conventional heat exchange: if the temperature of a heated surface increases, the net external heat flux to the surface will normally decrease not increase.

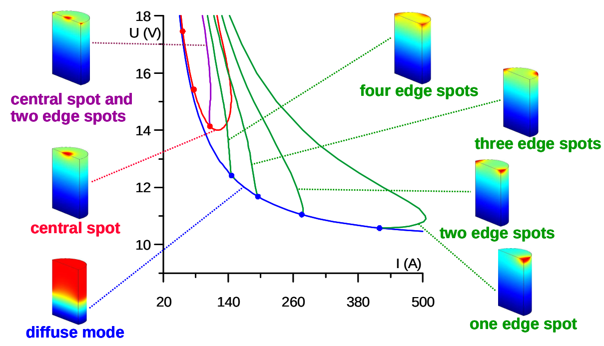

Fig. 3. Current-voltage characteristics of different steady-state modes and typical distributions of the temperature of the cathode surface associated with each mode. Rod W cathode, *R*=2mm, *h*=10mm, Ar plasma, *p*=1bar. Circles: bifurcation points.

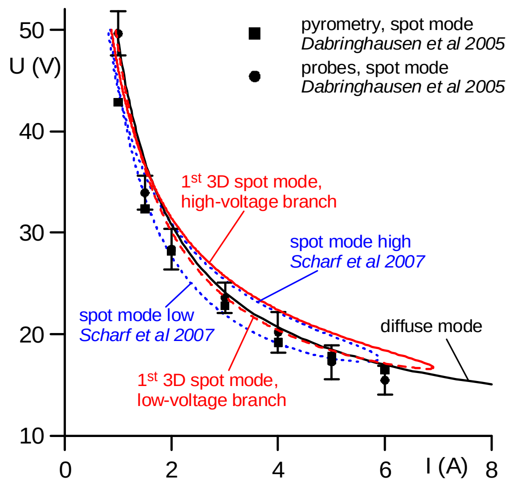

Fig. 4. Current-voltage characteristics. Rod W cathode, *R*=0.75mm, *h*=20mm, rounding 100µm, Ar plasma, *p*=2.6bar. Points: experiment [13].

B. Steady-State Modes of Current Transfer

Examples of calculation results for the plasma-cathode interaction on the whole are shown in Figs. 3 and 4. Fig. 3 shows data from [8] and [9] and refers to a cylindrical cathode of the radius *R*=2mm and the height *h*=10mm. Two of the modes shown in this figure are axially symmetric, one of these modes being the diffuse mode and the other being the first axially symmetric spot mode. The diffuse mode exists at all currents and its CVC (current-voltage characteristic) has two branches, one falling and the other rising, separated by a point of minimum [8]; only the falling branch is seen in Fig. 3. The first axially symmetric spot mode embraces steady states with a spot at the center of the front surface of the cathode and exists in a limited current range, I≤145A. The 3D modes shown in Fig. 3 are modes with one, two, three, or four spots at the edge of the front surface, and a mode with a spot at the center and two spots at the edge. The 3D modes also exist in limited current ranges.

Under conditions of Fig. 3, a value of the arc current exists for each 3D mode such that at this current the cathode temperature distribution associated with this mode turns axially symmetric and the corresponding state belongs to one of axially symmetric modes. This phenomenon, called bifurcation, or branching, of solutions, is well known in mathematical physics and frequently occurs in nonlinear systems admitting states of different symmetries. The 3D modes with spots at the edge branch off from the diffuse mode, and the mode with a spot at the center and two spots at the edge branches off from the first axially symmetric spot mode. Points at which this branching occurs coincide with bifurcation points predicted by the bifurcation theory [7], which are shown in Fig. 3 by circles.

The CVC shown in Fig. 4 by the solid and dashed lines has been calculated by means of the code [9]. The dotted line represents modeling results [10]. The CVCs of the spot mode calculated by two groups are in a good agreement, which adds credibility to the theory.

An extensive comparison with results of detailed electrical and thermal measurements has convincingly validated the model of nonlinear surface heating (e.g., [2], [6], [9], [11]–[15]); an example of such comparison is seen in Fig. 4.

C. Stability of Steady-State Modes of Current Transfer

In(stability) of steady-state modes of current transfer to thermionic cathodes of high-pressure arc discharges is a result of competition between a positive feedback, which is present on the growing section of the dependence of the density q of energy flux from the plasma on T_w the local surface temperature (see discussion of figure 2), and heat conduction in the cathode body, which tends to smooth out perturbations, i.e., produces a stabilizing effect.

A pattern of stability that has been established for a current-controlled arc on a rod cathode on the basis of an analytical treatment [16] and numerical results [17] is as follows. In all the cases, the spectrum of perturbations is real, which means a monotonic development or decay of perturbations. All modes other than the diffuse mode and the first 3D mode (the mode with one spot at the edge of the front surface of the cathode) are unstable, which includes modes with more than one spot and the axially symmetric mode with a spot at the center. The pattern of stability of the diffuse mode and the first 3D mode is shown in Fig. 5. The diffuse mode is stable beyond the first bifurcation point and unstable at lower currents. The low-voltage branch of the first 3D spot mode is unstable; the high-voltage branch is stable. The transition between the diffuse mode and the high-voltage branch of the first 3D spot mode is non-stationary and accompanied by hysteresis as shown by arrows. The first 3D spot mode on an axially symmetric cathode is neutrally stable against infinitesimal rotations.

D. On-line Tool for Simulation of Axially Symmetric Current Transfer to Rod Cathodes

A 2D simulation technique of plasma-cathode interaction has reached a point where it can be automated. A free on-line tool for simulation of axially symmetric steady-state current transfer to rod cathodes is available in the Internet [18]. The database of

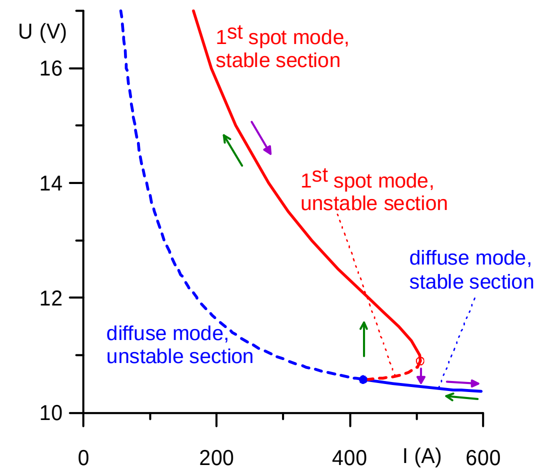

Fig. 5. Stable modes of current transfer to a cylindrical cathode of a current-controlled arc discharge and transitions between them. Rod W cathode, R=2mm, h=10mm, Ar plasma, p=1bar. Full circle: the first bifurcation point.

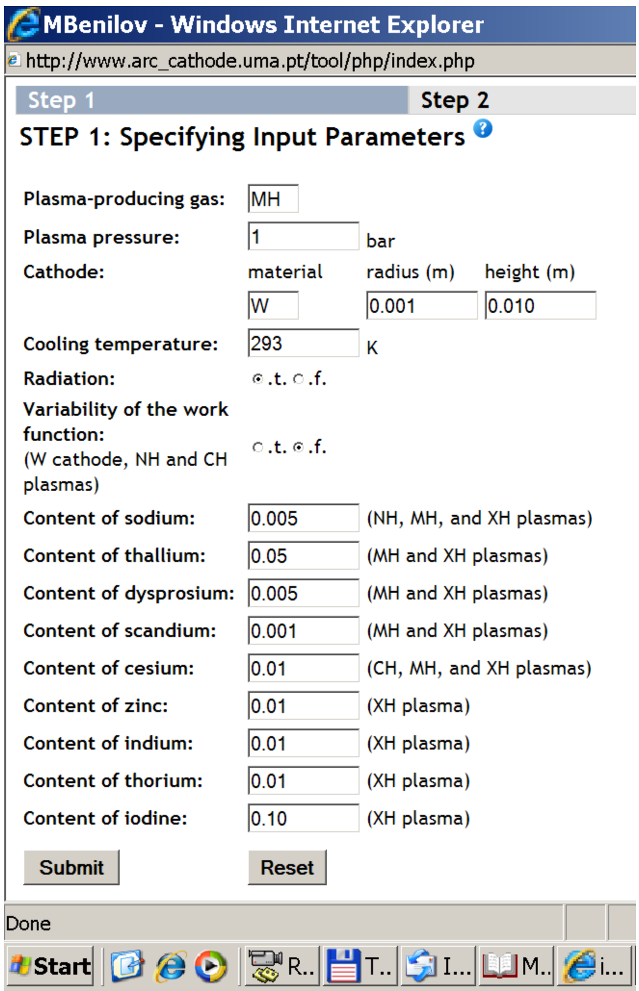

Fig. 6. Interface of the free on-line tool for simulation of axially symmetric steady-state current transfer to rod thermionic cathodes in high-pressure plasmas [18].

plasma-producing gases includes, but is not limited to, He, Ne, Na, Ar, Kr, Xe, Cs, Hg, air, mixtures Na-Hg and Cs-Hg, plasmas of mercury or xenon with addition of metal halides. The database of cathode materials includes W, Mo, Fe, Nb, Zr.

At present, the tool simulates the diffuse mode. Future versions will calculate bifurcation points positioned on the diffuse mode, including the first bifurcation point that represents the limit of stability of the diffuse mode, and simulate the first axially symmetric spot mode.

It should be stressed that the tool is destined not only for researchers but for engineers as well, so there is no need to study theoretical papers in order to be able to use the tool. The interface of the tool is shown in Fig. 6.

IV. Applying the Model of Nonlinear Surface Heating to Cathode Spots in Vacuum Arcs

There are two groups of theoretical models of plasma-cathode interaction in vacuum arcs: models based on considering this interaction as a collective phenomenon (e.g., reviews [19] and [20]), and models treating this interaction as a sequence of individual events, termed microexplosions, or microspots, or fragments, or "ectons" [19], [21]. Best developed at present are theoretical models of the first group. These models are not fundamentally different from the theoretical models of plasma-cathode interaction in high-pressure arcs. Therefore, the model of nonlinear surface heating may be applied in order to describe the plasma-cathode interaction also in vacuum arc discharges, its applicability being limited only by the assumption of a collective phenomenon. Clearly, the physics of the near-cathode plasma layer in vacuum arcs is different from that in high-pressure arc discharges: evaporation of the cathode material must be taken into account.

The above-described approach based on the model of nonlinear surface heating has been applied to copper cathodes of vacuum arcs in [22]. The dependence $q(T_w,U)$ for a copper cathode, calculated in [22], is shown in Fig. 7. One can see that this dependence is not qualitatively different from that typical for high-pressure arcs shown in Fig. 2, although numerical values are much higher. Characteristics of spots on copper cathodes of vacuum arcs, calculated by means of the model of nonlinear surface heating in [22], have been found [19] to reasonably agree with the experiment. Note that higher values of the energy flux from the plasma (the function q) in vacuum arcs explain smaller radii of cathode spots which are observed in experiments with vacuum arcs.

Since cathode spots in vacuum are small, they may be described by a model of a solitary current-collecting spot surrounded by a current-free region. However, the spot radius in most theoretical models either remains indeterminate or is determined with the use of empirical parameters or arbitrary theoretical assumptions, such as

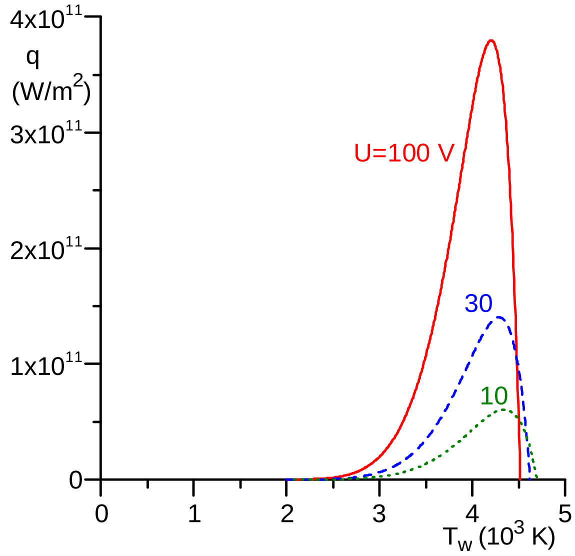

Fig. 7. Density of the net energy flux from a vacuum arc to the cathode cathode vs. the local surface temperature. Cu cathode.

some or other implementation of Steenbeck's "principle" of minimum power or considerations concerning processes on the plasma side. This is a consequence of a loss of information which occurs when a treatment of the differential thermal-conduction equation, which allows one to determine the temperature at every point of the cathode body, is replaced by only one finite equation, the equation of integral heat balance, which is insufficient to determine two parameters of a spot (its radius and temperature). Obviously, the lacking relationship should be sought where the loss of information has occurred, which is the treatment of thermal conduction in the cathode, and any attempt to derive it from unrelated considerations cannot be satisfactory; see discussion in [23].

The approach based on model of nonlinear surface heating allows one to solve this problem in a natural way: a model of a current-collecting spot surrounded by a current-free region can be self-consistently derived in the framework of such approach, including a relationship determining the spot radius [24]. Note that the latter relationship may be viewed as a condition of coexistence of phases, which is well known in theoretical physics, the roles of hot and cold phases being played by the current-collecting and, respectively, current-free sections of the cathode surface.

The model of nonlinear surface heating can in a natural way be modified in order to take into account melting of the cathode and deformation of its surface (for example, the growth of protrusions). This would require supplementing the heat-conduction equation inside the cathode with fluid dynamics equations, while the solution on the plasma side remains the same. Similarly, the model of nonlinear surface heating can in a natural way be modified in order to take into account Joule heating inside the cathode.

V. CONCLUSIONS

A self-consistent and universally accepted theory and simulation methods of the plasma-cathode interaction in high-pressure arc discharges have been developed and validated experimentally. The model of nonlinear surface heating, on which the theory and simulation methods are based, may be implemented as a part of theoretical models of plasma-cathode interaction in vacuum arcs which are based on considering this interaction as a collective phenomenon.

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