Physics of Spotless Mode of Current Transfer to Cathodes of Metal Vapor Arcs

Mikhail S. Benilov and Larissa G. Benilova

***Abstract*— A fresh attempt is made to clarify the physics of the diffuse, or spotless, mode of current transfer that may occur on cathodes of vacuum arcs if the average cathode surface temperature is high enough, about 2000 K. It is shown that in the case of chromium cathode the usual mechanism of current transfer to arc cathodes cannot sustain current densities of the order of 10^5–10^6 A · m^{-2} observed in the experiment, the reason being that the electrical power deposited into electron gas in the near-cathode space-charge sheath is insufficient. It is hypothesized that the electrical power is supplied to the electron gas primarily in the bulk plasma, rather than in the sheath, and a high level of electron energy in the vicinity of the sheath edge is sustained by electron heat conduction from the bulk plasma. Estimates of the current of ions diffusing to the sheath edge from the quasi-neutral plasma gave values comparable with the experimental current density, which supports the above hypothesis. On the contrary, the spotless attachment of vacuum arcs to gadolinium cathodes may be interpreted as a manifestation of the usual mechanism of current transfer to arc cathodes. Results given for gadolinium cathodes by a model of near-cathode layers in vacuum arcs conform to available experimental information.**

***Index Terms*— Arc discharges, electrodes, vacuum arcs.**

I. Introduction

IT IS well known that current transfer to cathodes of arc discharges in ambient gases may occur in the spot mode, where most of the current is localized in narrow domains, or current spots, occupying a small fraction of the cathode surface, and in the diffuse, or spotless, mode, where the current is distributed over the front surface of the cathode in a more or less uniform way. The diffuse mode is favored by high average temperature of the cathode surface, which can be achieved by reducing the cathode dimensions.

Spots on cathodes of vacuum, or metal vapor, arcs are known equally well. The spotless mode of current transfer to cathodes of vacuum arcs seems to be known not so well, however, its existence has been firmly established by now [1]–[7]. Similarly to the diffuse mode on cathodes of ambient-gas arcs, the spotless mode on cathodes of vacuum arcs occurs in cases where the average temperature of the cathode surface is high enough, typically around 2000 K. The latter can be achieved by placing the (evaporating) cathode into a thermally insulated crucible made of a material for which a vacuum arc would burn at a higher voltage than for the cathode material. Characteristic features of this discharge are a relatively low current density at the cathode, of the order of 10^5–10^6 A · m^{-2}, and the ability to generate steady highly ionized plasma containing no microdroplet fraction. The latter feature may be attractive for applications [6], [7].

Different spot and spotless modes on cathodes of ambient-gas arcs are described by a unified theory [8], which is based on the concept of self-organization in bistable nonlinear dissipative systems and applies not only to arc cathodes but also to cathodes of dc glow discharges. Recently, the same approach was applied to simulation of spots on cathodes of vacuum arcs [9], [10].

However, understanding of the spotless mode on cathodes of vacuum arcs remains elusive: it was concluded in the pioneer work [1] that none of the known mechanisms of current transfer to the cathode surface and, in particular, of the electron emission is capable of producing the above-mentioned current densities, and this conclusion still stands (except for cathodes made of Gd, which is characterized by a very low work function). Given that the effort invested by different groups in the experiment and its theoretical analysis has been quite significant [1]–[7], [11]–[15] and that the spotless arc attachment to cathodes, being in essence a 1-D and stationary phenomenon, represents a much simpler object than cathode spots, this state of the art is rather surprising and detrimental not only to potential applications of spotless vacuum arc discharges but also to the vacuum arc physics in general.

A fresh attempt to elucidate basic mechanisms of the spotless vacuum arc attachment to cathodes is undertaken in this paper.

II. Current Transfer to Cathodes in Thermal Plasmas

A. Nonemitting Cathodes

The plasma in the experiments [1]–[7] may be considered as a thermal plasma of saturated vapor of the cathode material. Ionization (Saha) equilibrium holds in the bulk of the plasma but is violated in a thin layer adjacent to the near-cathode space-charge sheath; the so-called ionization layer. If the ionization of neutral atoms occurs primarily in the quasi-neutral plasma, then the maximum ion current that can be

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The authors are with the Departamento de Física, Centro de Competência de Ciências Exatas e da Engenharia, Universidade da Madeira, Funchal 9000, Portugal, and also with the Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon 1649-004, Portugal (e-mail: benilov@uma.pt; larissa@uma.pt).

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extracted from the plasma (ion saturation current) is limited by ambipolar diffusion of the ions across the ionization layer. In the simplest case, where the ions in the ionization layer are predominantly singly charged and variations of the temperatures of the electrons and the heavy particles, T_e and T_h, are negligible in the ionization layer, the ion saturation current may be estimated analytically [16]

$$j_i = eD_a \frac{n_i^{(S)}}{d}, \quad D_a = D_{ia}\left(1 + \frac{T_e}{T_h}\right), \quad d = C\sqrt{\frac{D_a k T_h}{k_i p}}. \tag{1}$$

Here, D_{ia} is the coefficient of binary diffusion of the ions and the atoms; $n_i^{(S)}$ is the charged particle density at the edge of the ionization layer, which may be evaluated by means of the Saha equation in terms of T_e, T_h, and the plasma pressure p; C is a numerical coefficient which depends on the ratio T_e/T_h and the ionization degree at the edge of the ionization layer and varies between 1.49 and 1; and k_i is the ionization rate constant (a function of T_e). Note that D_a has the meaning of the ambipolar diffusion coefficient, d is usually called the ionization length and represents a scale of thickness of the ionization layer.

To evaluate the ion current by means of (1), one needs to specify T_e, T_h, and p. It is natural to assume that the heavy particle temperature T_h equals the cathode surface temperature T_w and to set p equal to the pressure of saturated vapor of the cathode material at the temperature T_w.

The mechanism of energy exchange in the near-cathode region needs to be identified to understand how T_e should be properly specified. The case considered in this section is the one where the temperature of the cathode surface is not sufficiently high to produce appreciable electron emission and the current is transported to the cathode surface by ions entering the sheath from the ionization layer. This regime is similar to the ion current regime of electrostatic (Langmuir) probes. The power deposited by the arc power supply into the near-cathode space-charge sheath is transported by the ions to the cathode. A high level of electron temperature in the ionization layer, which is necessary to sustain a sufficiently high charged-particle density and, consequently, a sufficiently high ion current to the cathode, is ensured by electron heat conduction from the bulk plasma. It is necessary to analyze the electron energy balance of the bulk plasma to self-consistently determine the electron temperature in the ionization layer and thus the ion current.

B. Emitting Cathodes

Under typical conditions of arc discharges, the temperature of the cathode surface is sufficiently high to produce an appreciable electron emission. The ion current in such conditions constitutes a few tenths (usually no more than 0.3) of the net current. Hence, a few tenths of the power deposited into the near-cathode space-charge sheath goes to the ions and is transported to the cathode surface. This power ensures heating of the cathode up to temperatures sufficient for electron emission. The rest of the deposited power goes to the electrons. This power is partly spent in the near-cathode region on ionization of neutral atoms, which should be sufficient for providing the necessary ion current, and partly is transported into the bulk plasma by the electron current.

The latter means that the flux of electron energy is directed not from the bulk plasma to the near-cathode layer, as in the case of nonemitting cathodes, but rather the other way round. Therefore, balance of electron energy in the near-cathode layer may be evaluated and the local electron temperature found independently of the bulk plasma. This is the approach employed in models of near-cathode layers in arc discharges both in ambient gases and vacuum (see [17] and references therein and [18]–[20], respectively). In addition to the ion current, such models compute also the electron emission current with account of Schottky correction or thermo-field emission mechanism and the current of plasma electrons reaching the cathode against the retarding electric field in the space-charge sheath.

One can conclude that there is a substantial difference between evaluation of current transfer to cathodes in thermal plasmas in the cases of emitting and nonemitting cathodes. A relevant model of near-cathode layer in arc discharges may be employed in the former case. In the latter case, the ion current to the cathode cannot be self-consistently evaluated from analysis of the near-cathode region only, without evaluation of the electron energy balance of the bulk plasma. This difference stems from the opposite directions of transport of electron energy: it is transported by the electron current in the direction from the near-cathode region into the bulk plasma in the case of emitting cathode, while in the case of nonemitting cathode the energy is transported by electron heat conduction in the direction from the bulk plasma into the near-cathode region.

III. Chromium Cathode

The cathode material on which many experiments have been performed is chromium [1], [5], [7]. In this section, estimates of current transfer to chromium cathodes in conditions of these experiments are made on the basis of the qualitative considerations given in Section II.

Let us first assume that the electron emission from the cathode is significant. As discussed in Section II-B, one can perform a self-consistent evaluation by means of a relevant model of near-cathode layers in arc discharges in this case. In this paper, the model of near-cathode layers in vacuum arcs [20] is used. Note that a characteristic feature of near-cathode layers in vacuum arcs is the ionization of evaporated metal atoms occurring primarily in the outer section of the near-cathode space-charge sheath, rather than in the quasi-neutral plasma (ionization layer) as in the case of nonemitting cathodes discussed in Section II-A. This feature is reflected in the model [20], which comprises a self-consistent description of the space-charge sheath with ionization of evaporated atoms and with a maximum of potential occurring inside the sheath. Also considered is balance of the evaporated metal atoms with their eventual return to the cathode if ionized before the potential maximum, as well as balance of the electron energy.

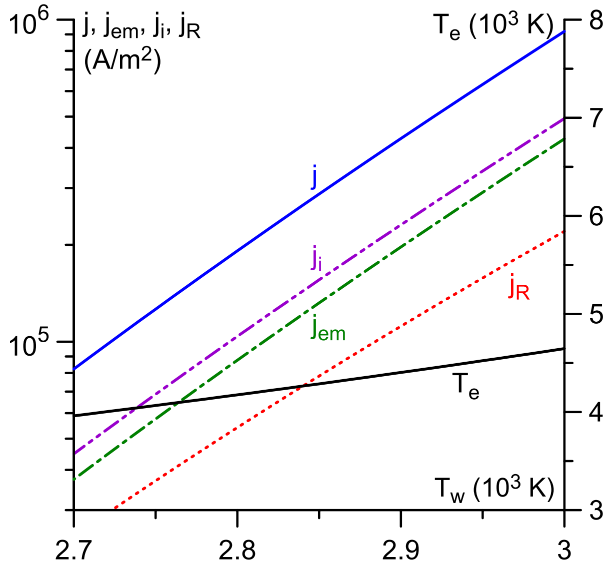

Fig. 1. Calculations with account of conventional mechanisms of current transfer to cathodes of vacuum arcs. Chromium cathode, sheath voltage $U = 20$ V.

The results of calculations performed by means of the model [20] are shown in Fig. 1. (Here, j_i is the density of ion current to the cathode surface, j_{em} is the density of electron emission current, j is the net current density, j_R is the thermionic emission current density evaluated by means of the Richardson formula, and T_e is the temperature of electrons in the near-cathode layer.) The material constants for Cr cathodes were set as described in [20]. The work function A_f in these calculations was set equal to 4.58 eV; a value for polycrystalline chromium surface recommended in [21]. (This value is given also in [22] and a similar value of 4.5 eV is given in [23].)

One can see that the density of current of ions coming to the cathode surface from the space-charge sheath slightly exceeds the electron emission current density. The electric field at the cathode surface is not high enough for the thermo-field electron emission mechanism to come into play and the electron emission is of thermionic nature. Therefore, the electron emission current density j_{em} shown in Fig. 1 (which was evaluated by means of the Murphy and Good formalism) is very well represented by the Richardson–Dushmann formula. On the other hand, j_{em} exceeds the Richardson value j_R; hence, the Schottky correction to the work function is appreciable (e.g., 0.13 eV for $T_w = 2850$ K). The current of the fast plasma electrons capable of overcoming the retarding electric field of the sheath and reaching the cathode surface is negligible and not seen on the graph.

Although the density j of net electric current at the cathode surface exceeds the Richardson value j_R by a factor of 3–4, this difference is insufficient to bring the estimates close to the experiment: j attains the value of 10^5 $\mathrm{A \cdot m^{-2}}$ at $T_w \gtrsim 2700$ K, which is significantly higher than the measured temperatures around 2000 K.

A natural question is if the value $A_f = 4.58$ eV of the work function of chromium, used in calculations shown in Fig. 1, is adequate under conditions being considered. Reference [24] makes an explicit distinction between thermionic and photoelectric work functions; for chromium, the values of 3.90 eV are given for the former and of 4.4 eV for the latter. Without discussing the reliability of these data (while the thermionic and photoelectric work functions differ in semiconductors, they are usually considered to be the same in metals), we only note that the calculations similar to those shown in Fig. 1 but with $A_f = 3.90$ eV [15] gave results that are closer to the experiment, however, the difference is still significant.

Thus, the estimates have indicated that the usual mechanism of current transfer to vacuum arc cathodes in the case of chromium cathode cannot sustain current densities of the order of 10^5–10^6 $\mathrm{A \cdot m^{-2}}$ observed in the spotless attachment [1], [5], [7]. The reason may be understood from very low values of the electron temperature T_e and the corresponding ionization degree in the near-cathode layer predicted by the model (see curve T_e in Fig. 1): 3960 K and 2.3×10^{-3}, respectively, for $T_w = 2700$ K and still lower for smaller T_w. Since the plasma is highly ionized under the experimental conditions [1], [5], [7], these values clearly are unrealistically low. One should conclude that work of the electric field over the emitted electrons inside the sheath, which is the main source of electron energy in the near-cathode layer in the model [20], is insufficient to maintain an appreciable ionization degree due to very low electron emission current.

It follows that the usual mechanism of current transfer to vacuum arc cathodes is irrelevant in the case of spotless attachment to chromium cathodes and one should consider the case of nonemitting cathode, discussed in Section II-A. A question arises if the density of the bulk plasma under the experimental conditions [1], [5], [7] is sufficiently high to ensure the density of ion current to the cathode of the order of 10^5–$10^6\ \mathrm{A \cdot m^{-2}}$. As discussed in Section II, the electron temperature T_e in the near-cathode layer in the case of nonemitting cathode is governed by electron heat conduction from the bulk plasma (rather than by a local energy supply as assumed in computations shown in Fig. 1) and a self-consistent determination of T_e would involve an evaluation of the electron energy balance of the bulk plasma. Leaving such evaluation beyond the scope of this paper, we will set T_e equal to 8000 K: at this value the Cr plasma under the pressure of 1 mbar (which is the pressure of saturated Cr vapor at the cathode temperature of 2000 K) approaches full ionization. The ion current density computed by means of (1) with the use of this value is depicted by the curve marked $j_i^{(d)}$ in Fig. 2. (In these calculations the pressure of saturated vapor of Cr and the ionization rate constant have been estimated, as described in [20], and the ion-atom binary diffusion coefficient was estimated in terms of the resonant charge exchange cross section given in [22]). One can see that the ion current density is of the same order of magnitude as the experimental current density.

Also shown in Fig. 2 is the ionization length d, the Debye length λ_D, and the mean free path for collisions between the ions and neutral atoms $\lambda_{ia} = [(n_a^{(S)} + n_i^{(S)})\bar{Q}_{ia}^{(1,1)}]^{-1}$, where $n_a^{(S)}$ is the number density of the atoms at the edge of the ionization layer and $\bar{Q}_{ia}^{(1,1)}$ is the average cross section

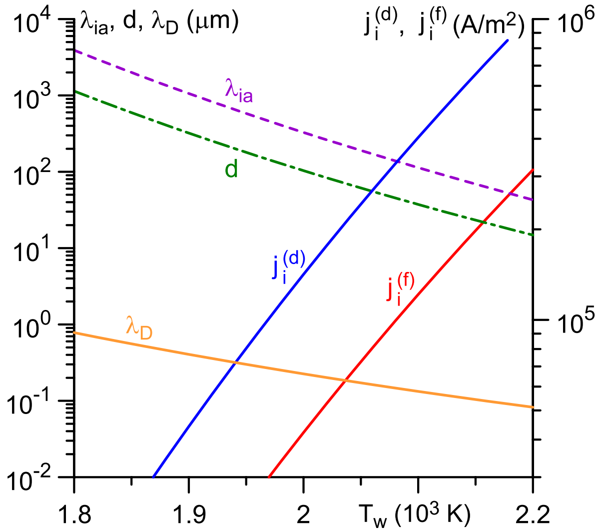

Fig. 2. Ion saturation current. Chromium-vapor plasma, $T_e = 8000\,\text{K}$. $j_i^{(d)}$: diffusion evaluation. $j_i^{(f)}$: multifluid evaluation.

for momentum transfer in ion-atom collisions. Conditions of the validity of (1) read $\lambda_D, \lambda_{ia} \ll d \ll L$, where L is a characteristic dimension of the plasma. Given that L is of the order of 1 cm in the conditions of experiments [1]–[7], one can see that the inequalities $\lambda_D \ll d \ll L$ are satisfied but the inequality $\lambda_{ia} \ll d$ is not; in fact, λ_{ia} exceeds d by a factor of about 3. An approximate theory for such conditions was developed by means of the so-called multifluid approach [25]. The ion current evaluated by means of [25, eq. (50)] with the coefficient C_1 replaced by C_2 given by [16, eq. (14)] is depicted by the curve marked $j_i^{(f)}$ in Fig. 2. Although $j_i^{(f)}$ is smaller than the diffusion value $j_i^{(d)}$, it is still not far away from the experiment: $j_i^{(f)}$ exceeds $10^5\,\text{A}\cdot\text{m}^{-2}$ for $T_w \gtrsim 2100\,\text{K}$.

Thus, estimates of the ion saturation current give values consistent with the assumption that the current in the spotless attachment of vacuum arc to chromium cathode is transported by ions diffusing to the sheath edge from the quasi-neutral plasma.

IV. Gadolinium Cathode

A significant amount of experimental data on spotless vacuum arc attachment has been obtained for cathodes made of gadolinium [2]–[4], [6], [7]. The value of work function recommended in [21] for a polycrystalline surface of gadolinium is 3.1 eV, i.e., quite low, and a still lower value of 2.9 eV is given in [23]. Accordingly, it is well known that thermionic emission current is high enough to ensure the spotless attachment of vacuum arcs to a gadolinium cathode observed in the experiments [2]–[4], [6], [7]. However, it is of interest to apply to gadolinium cathodes the same approach that was applied above to cathodes made of chromium, to once again validate the approach and demonstrate the possibility of self-consistent calculation of some parameters of the spotless vacuum arc on a gadolinium cathode.

The results of calculations for gadolinium cathodes are shown in Figs. 3 and 4. (In these calculations, work function

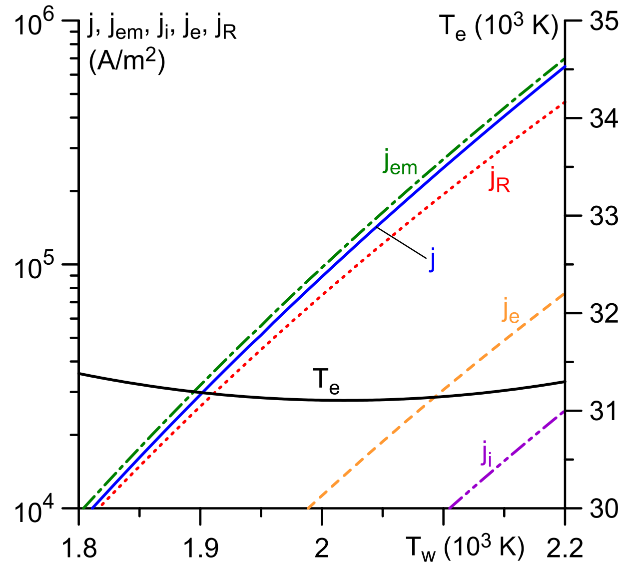

Fig. 3. Same as Fig. 1, gadolinium cathode, $U = 10\,\text{V}$.

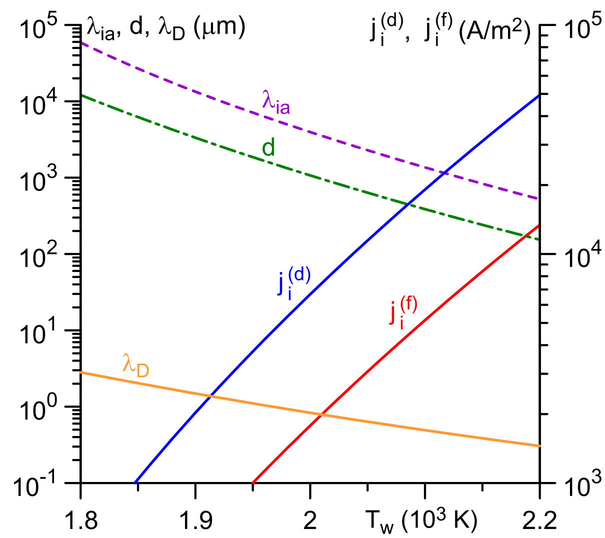

Fig. 4. Same as Fig. 2, gadolinium-vapor plasma, $T_e = 8000\,\text{K}$.

of Gd was set equal to 3.1 eV, the pressure of saturated vapor of Gd has been estimated according to [23], the ionization rate constant was evaluated as described in [25] with the use of the cross section of direct ionization of Gd atoms from [26], and the ion-atom diffusion coefficient and the average cross section $\bar{Q}_{ia}^{(1,1)}$ were evaluated in terms of the resonant charge exchange cross section given in [22]). One can see that the current density computed by means of the model of near-cathode layers in vacuum arcs [20] (curve j in Fig. 3) exceeds $10^5\,\text{A}\cdot\text{m}^{-2}$ for $T_w \gtrsim 2000\,\text{K}$, i.e., is in the right order of magnitude. On the other hand, the ion saturation current from the Gd-vapor plasma ($j_i^{(f)}$ in Fig. 4) does not exceed approximately $10^4\,\text{A}\cdot\text{m}^{-2}$. It follows that the spotless attachment of vacuum arcs to gadolinium cathodes is a manifestation of the usual mechanism of current transfer to vacuum arc cathodes and cannot be explained by current of ions diffusing from the quasi-neutral plasma, in contrast to the case of chromium cathodes.

Let us consider in some detail results given by the model described in [20] and shown in Fig. 3. The electron temperature in the near-cathode layer is around 3.1×10^4 K, i.e., rather high, and is still higher for higher values of the sheath voltage; e.g., $T_e \approx 6.3 \times 10^4$ K for $U = 20$ V. This is a consequence of the significant electrical power supplied to the electron gas in the sheath, which, in turn, originates in the significant electron-emission current.

The net current density j is close to j_{em} and slightly bigger than j_R. Current transported by fast plasma electrons attaining the cathode (curve j_e) is about 12% of the net current density, while the ion current j_i is about 4%. It should be stressed that the smallness of j_i is not a consequence of the return of most part of evaporated atoms to the cathode in the form of ions; e.g., for $T_w = 2000$ K about 43% of the ions are produced after the potential maximum in the sheath and escape into the plasma. Rather, the smallness of the contribution of the ion current originates in the well known [2]–[4], [6], [7] fact that the flux of emitted electrons from a gadolinium surface is significantly higher than the flux of evaporated atoms, which results from the low work function of gadolinium and relatively high evaporation energy. (The latter equals 3.73 eV per atom [22]; for comparison, values for Cr and Cu are 3.55 and 3.16 eV, respectively [24].)

Values of the ratio j_i/j_{em} that low are unusual for arc cathodes and mean that the cooling of the cathode by electron emission exceeds heating by the ion current. Therefore, a possible source of heating of gadolinium cathodes in the experiments [2]–[4], [6], [7] is radiation from the plasma.

Another consequence of low values of the ratio j_i/j_{em} may be the necessity to take into account contribution of the emitted electrons to space charge in the near-cathode sheath [27], which is neglected in the model [20]. Note, however, that the above-mentioned values of this ratio are still by an order of magnitude higher than the minimal value corresponding to the formation of a virtual cathode, which equals the square root of the electron-to-ion mass ratio (e.g., [27]) and for gadolinium is approximately 0.2%.

The above results conform to experimental information and estimates available in the literature. In particular, the electron temperature measured in Gd is around 3–4 eV for the arc voltage $V_a = 10$ V and increases to 7–8 eV for $V_a = 20$ V [6, Fig. 9]. The spectral line of doubly charged ions has been observed in Gd and its intensity was found to decrease with increasing V_a; a possible indication to the presence of triply charged ions (which are abundant at T_e that high) [7]. It should be stressed that only lines of atoms and singly charged ions have been observed in Cr plasma [7]. The ion current to a gadolinium cathode does not exceed 5% of the electron-emission current [4].

V. Conclusion

Qualitative reasoning and calculations have shown that the usual mechanism of current transfer to arc cathodes, characterized by a large electric power deposited by the arc power supply into the electron gas in the near-cathode space-charge sheath, in the case of chromium cathode cannot sustain current densities of the order of 10^5–$10^6\,\mathrm{A \cdot m^{-2}}$ observed in the spotless attachment. The root reason is that the power deposited into the electron gas in the sheath is insufficient in this case, which originates in very low electron-emission current. One should hypothesize therefore that the electrical power is supplied to the electron gas primarily in the bulk plasma, rather than in the sheath, and the current is transported to chromium cathode by ions diffusing to the sheath edge from the quasi-neutral plasma across the ionization layer; a regime similar to the ion current regime of electrostatic probes in thermal plasmas. Estimates of the ion current gave values comparable to the experimental current density, which supports the above hypothesis.

In contrast to the case of chromium cathodes, the spotless attachment of vacuum arcs to gadolinium cathodes should be viewed as a manifestation of the usual mechanism of current transfer to arc cathodes and cannot be explained by current of ions diffusing to the sheath edge from the bulk plasma. The results given for gadolinium cathodes by a model of near-cathode layers in vacuum arcs conform to experimental information and estimates available in the literature. The computed ratio of the ion current to the electron-emission current is about 0.04, which is significantly smaller than values of this ratio characteristic of current transfer to arc cathodes. Therefore, cooling of the cathode by electron emission prevails over heating by ion current and a possible mechanism of heating of gadolinium cathodes in the experiments with spotless arc attachment is radiation from the plasma.

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References

[1] A. I. Vasin, A. M. Dorodnov, and V. A. Petrosov, "Vacuum arc with a distributed discharge on an expendable cathode," *Soviet Tech. Phys. Lett.*, vol. 5, pp. 634–636, Dec. 1979.

[2] S. N. Paranin, V. P. Polishchuk, P. E. Sychev, V. I. Shabashov, and I. M. Yartsev, "Thermal conditions in a hot evaporating cathode in a stationary vacuum arc with diffuse cathode emission," *High Temperature*, vol. 24, no. 3, pp. 307–313, 1986.

[3] V. P. Polishchuk, P. E. Sychev, V. I. Shabashov, and I. M. Yartsev, "Anchoring of a steady vacuum arc on a hot thermionic cathode," *Soviet Tech. Phys. Lett.*, vol. 31, no. 11, pp. 1336–1337, 1986.

[4] S. Ya, Bronin, V. P. Polishchuk, P. E. Sychev, V. I. Shabashov, and I. M. Yartsev, "Rate of cathode evaporation and plasma parameters in a steady vacuum-arc," *High Temperature*, vol. 31, no. 1, pp. 33–41, 1993.

[5] V. M. Batenin, I. I. Klimovskii, V. P. Polishchuk, and V. A. Sinel'shchikov, "A stationary vacuum arc with a diffuse spot on a nonemitting chrome cathode," *High Temperature*, vol. 41, no. 5, pp. 586–593, Sep. 2003. [Online]. Available: http://dx.doi.org/10.1023/A:1026132325564

[6] R. Amirov *et al.*, "Investigation of plasma flow in vacuum arc with hot cathode," *J. Phys., Conf. Ser.*, vol. 550, no. 1, p. 012014, 2014. [Online]. Available: http://stacks.iop.org/1742-6596/550/i=1/a=012014

[7] R. K. Amirov *et al.*, "Prototypical plasma source for technology of plasma separation of spent nuclear fuel," in *Proc. Conf. Phys. Low-Temperature Plasma FNTP*, vol. 1. 2014, pp. 130–134.

[8] M. S. Benilov, "Multiple solutions in the theory of dc glow discharges and cathodic part of arc discharges. Application of these solutions to the modeling of cathode spots and patterns: A review," *Plasma Sour. Sci. Technol.*, vol. 23, no. 5, p. 054019, 2014. [Online]. Available: http://stacks.iop.org/0963-0252/23/i=5/a=054019

[9] M. S. Benilov, M. D. Cunha, W. Hartmann, S. Kosse, A. Lawall, and N. Wenzel, "Space-resolved modeling of stationary spots on copper vacuum arc cathodes and on composite CuCr cathodes with large grains," *IEEE Trans. Plasma Sci.*, vol. 41, no. 8, pp. 1950–1958, Aug. 2013. [Online]. Available: http://dx.doi.org/10.1109/TPS.2013.2263255

[10] M. S. Benilov, M. D. Cunha, W. Hartmann, and N. Wenzel, "Numerical investigation of the stability of stationary solutions in the theory of cathode spots in arcs in vacuum and ambient gas," *Plasma Sour. Sci. Technol.*, vol. 23, no. 5, p. 054007, 2014. [Online]. Available: http://stacks.iop.org/0963-0252/23/i=5/a=054007

[11] V. F. Puchkarev and S. M. Chesnokov, "Erosion rate and voltage distribution in contracted (with cathode spot) and diffuse (spotless) low-current vacuum arcs," *J. Phys. D, Appl. Phys.*, vol. 25, no. 12, p. 1760, 1992. [Online]. Available: http://stacks.iop.org/0022-3727/25/i=12/a=011

[12] A. V. Bolotov, A. V. Kozyrev, and Y. D. Korolev, "Model for the cathode layer of vacuum arc at nonmonotonical distribution of a potential in a near-cathode plasma," *Fizika Plasmy*, vol. 19, no. 5, pp. 709–719, 1993.

[13] A. Bolotov, A. Kozyrev, and Y. Korolev, "A physical model of the low-current-density vacuum arc," *IEEE Trans. Plasma Sci.*, vol. 23, no. 6, pp. 884–892, Dec. 1995. [Online]. Available: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=476470

[14] M. S. Benilov, "On investigation of the physics of near-cathode layers of the metal vapor arcs," in *Progress in Plasma Processing of Materials*, P. Fauchais, Ed. New York, NY, USA: Begell House, 1997, pp. 815–821.

[15] M. S. Benilov and L. G. Benilova, "Analyzing spotless mode of current transfer to cathodes of metal-vapor arcs," in *Proc. 26th Int. Symp. Discharges Elect. Insul. Vac.*, Mumbai, India, Sep./Oct. 2014, pp. 241–244.

[16] M. S. Benilov, "Analysis of ionization non-equilibrium in the near-cathode region of atmospheric-pressure arcs," *J. Phys. D, Appl. Phys.*, vol. 32, no. 3, pp. 257–262, 1999. [Online]. Available: http://stacks.iop.org/0022-3727/32/i=3/a=013

[17] M. S. Benilov, "Understanding and modelling plasma–electrode interaction in high-pressure arc discharges: A review," *J. Phys. D, Appl. Phys.*, vol. 41, no. 14, pp. 144001-1–144001-30, 2008. [Online]. Available: http://stacks.iop.org/0022-3727/41/144001

[18] I. Beilis, "Theoretical modeling of cathode spot phenomena," in *Handbook of Vacuum Arc Science & Technology: Fundamentals and Applications*, R. L. Boxman, D. M. Sanders, and P. J. Martin, Eds. Park Ridge, NJ, USA: Noyes, 1995, pp. 208–256.

[19] D. L. Shmelev, T. Delachaux, and E. Schade, "Kinetic numerical simulation of the cathode attachment zone of constricted high-current vacuum arcs," *IEEE Trans. Plasma Sci.*, vol. 41, no. 2, pp. 384–390, Feb. 2013.

[20] N. A. Almeida, M. S. Benilov, L. G. Benilova, W. Hartmann, and N. Wenzel, "Near-cathode plasma layer on CuCr contacts of vacuum arcs," *IEEE Trans. Plasma Sci.*, vol. 41, no. 8, pp. 1938–1949, Aug. 2013. [Online]. Available: http://dx.doi.org/10.1109/TPS.2013.2260832

[21] V. S. Fomenko, *Emission Properties of Materials*, 4th ed. Kiev, Ukraine: Naukova Dumka, 1981.

[22] I. S. Grigoriev and E. Z. Meilikhov, Eds., *Handbook of Physical Quantities*. Boca Raton, FL, USA: CRC Press, 1997.

[23] D. R. Lide, Ed., *CRC Handbook of Chemistry and Physics*, 84th ed. Boca Raton, FL, USA: CRC Press, 2004.

[24] W. F. Gale and T. C. Totemeier, Eds., *Smithells Metals Reference Book*, 8th ed. Amsterdam, The Netherlands: Elsevier, 2004.

[25] M. S. Benilov and G. V. Naidis, "Ionization layer at the edge of a fully ionized plasma," *Phys. Rev. E*, vol. 57, no. 2, pp. 2230–2241, Feb. 1998. [Online]. Available: http://link.aps.org/doi/10.1103/PhysRevE.57.2230

[26] H. Seo, M. G. Pia, P. Saracco, and C. H. Kim, "Ionization cross sections for low energy electron transport," *IEEE Trans. Nucl. Sci.*, vol. 58, no. 6, pp. 3219–3245, Dec. 2011.

[27] P. D. Prewett and J. E. Allen, "The double sheath associated with a hot cathode," *Proc. R. Soc. Lond. A, Math. Phys. Sci.*, vol. 348, no. 1655, pp. 435–446, 1976. [Online]. Available: http://dx.doi.org/10.1098/rspa.1976.0048

Mikhail S. Benilov received the Diploma (Hons.) and C.Sc. (Ph.D.) degrees in physics from the Moscow Institute for Physics and Technology, Moscow, Russia, in 1974 and 1978, respectively, and the Doctor of Physical and Mathematical Sciences degree from the Institute for High Temperatures, Russian Academy of Sciences, Moscow, in 1990. His thesis was concerned with the theory of electrostatic probes and electrodes in high-pressure flowing plasmas.

He was with the Institute for High Temperatures, Russian Academy of Sciences, where he led a group in plasma and nonlinear physics, numerical modeling, and fluid dynamics, after completing postgraduate courses with the Moscow Institute for Physics and Technology and the Institute for Mechanics, Lomonosov Moscow State University, Moscow, in 1977. He stayed for two years with Ruhr-Universität Bochum, Bochum, Germany, where he was involved in the theory and simulation of near-electrode phenomena. Since 1993, he has been a Professor and the Chair of the Department of Physics with the Universidade da Madeira, Funchal, Portugal. His current research interests include plasma physics, in particular, plasma-electrode interaction, nonlinear physics, and numerical modeling.

Larissa G. Benilova received the Degree in electrical engineering from the Moscow Institute of Railway Engineering, Moscow, Russia.

She was with several computing centers in Moscow and Bochum, Germany, from 1975 to 1996. From 1997 to 1999, she was involved in scientific programming and word processing with the Instituto Superior Técnico, Lisbon, Portugal. Since 2001, she has been contracted by the Universidade da Madeira, Funchal, Portugal, as an Engineer-Programmer, and has performed scientific programming and numerical simulations in the framework of a number of research projects in plasma science and applications funded by the European Union, the Fundação para a Ciência e a Tecnologia of Portugal, Philips Technologie GmbH, and Siemens AG. She has co-authored a number of papers in research journals and conference proceedings.