

THEORY OF A CATHODIC PART OF HIGH-PRESSURE ARC DISCHARGES

M. S. Benilov† and A. Marotta‡

†Departamento de Física, Universidade da Madeira
Largo do Município, 9000 Funchal, Portugal

‡Instituto de Física 'Gleb Wataghin', Universidade Estadual da
Campinas - UNICAMP, 13083 - 970, Campinas, São Paulo, Brazil

The paper deals with calculation of parameters in the near-cathode plasma layer, on the cathode surface and in the body of a cathode in high-pressure arc discharges. A model of a near-cathode layer is developed which is based on a multifluid description of the plasma and takes into account multiply charged ions. An approximate asymptotic theory of arc spots is extended to spots on planar cathode in high-pressure plasmas. The obtained results agree with the recent experimental data.

1. Introduction. Investigations on the theory of current transfer to cathodes in high-pressure arcs may be divided into two groups. The first group comprises studies that combine some or other model of the near-cathode plasma layer with a model of heat transfer in the cathode body; see, e.g., [1, 2]. Note that most of these studies were incomplete; in particular, they were unable to predict a radius of the cathode spot without using empirical parameters or rather arbitrary theoretical suppositions.

The second group comprises recent investigations in which current transfer to a cathode is calculated in the course of numerical treatment of the entire system arc-cathode, including the arc column, the near-cathode plasma layer and the cathode body [3, 4, 5, 6]. While the physics of the near-cathode layer implemented in the model [3, 6] is in the spirit of the physics considered conventionally in the framework of the first approach mentioned above, the physics [4, 5] is essentially different (in particular, the space-charge sheath is disregarded).

Recently a self-consistent way to determine the radius of an arc spot has been found and applied in the framework of the macroscopic theory of vacuum arc spots [7]. The aim of the present paper is to apply this method to high-pressure arcs and to develop a closed model of arc spots on planar cathodes.

2. The space-charge sheath. We consider a conventional model including the collisionless space-charge sheath and the quasineutral ionization layer. The role of the space-charge sheath consists in suppressing the flux of the electrons "counterdiffusing" from the quasineutral plasma to the cathode surface and

in acceleration of the emitting electrons, thus increasing the energy influx into the ionization layer. Hence, any model that disregards the sheath, in particular, the model [5] may encounter difficulties with the electric current balance and the energy balance. Indeed, a simple estimate of the current of the plasma electrons, which is disregarded in [5], shows that this current is by two orders of magnitude larger than the ion current. This means that the total electric current in the conditions considered in [5] is directed from the cathode to the plasma, which, of course, does not make sense. A probable explanation of the fact that the energy balance in the model [5] is satisfied without acceleration of the emitted electrons in the space-charge sheath is that the energy equation [5] disregards the ionization losses and the enthalpy transport due to the electric current.

The spatial distribution of the number density of the plasma electrons in the sheath is described by the Boltzmann factor, the ion density may be found by integrating the kinetic equation with the boundary condition taken from [8]

$$n_e = n_{es} \exp \frac{e\varphi}{kT_e}, \quad n_i = n_{is} \frac{v_+ - v_-}{2u_i}, \quad v_{\pm} = \left\{ \left[\sqrt{\frac{k(T_i + ZT_e)}{m_i}} \pm u_i \right]^2 - \frac{2Ze\varphi}{m_i} \right\}^{1/2}.$$

Here Z is a charge number of the ions, $u_i = \sqrt{kT_i/m_i}$, and index s is attributed to values at the sheath edge.

The electric field may be found by means of the Poisson equation

$$\frac{d\varphi}{dy} = \left\{ \frac{2n_{is}}{\epsilon_0} \left[m_i \left(\frac{v_+^3 - v_-^3}{6u_i} - \frac{4kT_i}{3m_i} - \frac{ZkT_e}{m_i} \right) - ZkT_e \left(1 - \exp \frac{e\varphi}{kT_e} \right) \right] \right\}^{1/2}.$$

Electric current density in the sheath is transported by the ions, emitted electrons, and the counterdiffusing plasma electrons: $j = j_i + j_{em} - j_e$. One has

$$j_i = eZn_{is} \sqrt{\frac{k(T_i + ZT_e)}{m_i}}, \quad j_e = \frac{en_{es}}{4} \left(\frac{8kT_e}{\pi m_e} \right)^{1/2} \exp \left(-\frac{eU_D}{kT_e} \right),$$

where U_D is the voltage drop in the space-charge sheath. The electron emission flux may be estimated in terms of the work function A , the surface temperature T_w , and the electric field at the surface.

The energy flux coming from the sheath to the cathode surface equals

$$q = \frac{j_i}{Ze} \left\{ k \left[2T_i + \frac{ZT_e}{2} + 2(Z-1)T_w \right] + ZeU_D + E \right\} + 2 \frac{j_e}{e} k(T_e - T_w) - \frac{j}{e} \tilde{A}_{eff}.$$

Here $\tilde{A}_{eff} = A - \Delta A + 2kT_w$, ΔA is the Schottky correction, and E is the ionization energy.

3. The ionization layer. Estimates show that the mean free path ion-neutral is not small as compared to the layer thickness. This means that coupling between the ions and the neutrals is not strong enough and a conventional diffusion description of the plasma, i.e., a model of a fluid with diffusing species, is not justified [9]. We shall employ the correlation formula obtained in the framework of a multifluid model [9]:

$$n_{is} = n_{i\infty} \frac{0.8}{2 + \alpha}, \quad \alpha = \left(\frac{kT_i}{m_i D_{ia\infty} k_r n_{i\infty}^2} \right)^{1/2}.$$

Here $n_{i\infty}$ and $D_{ia\infty}$ are the (equilibrium) ion density and the diffusion coefficient ion-neutral, evaluated at the edge of the ionization layer.

The voltage drop in the ionization layer is $U_i = \frac{kT_e}{e} \ln \frac{n_{e\infty}}{n_{es}}$. The total voltage drop in the near-cathode layer equals $U = U_D + U_i$.

The equation of balance of the electron energy in the ionization layer accounts for the energy brought in the layer by the emitted electrons accelerated in the space-charge sheath, the work of the electric field over the electrons inside the layer, the energy carried away by the electrons leaving the ionization layer, and losses for ionization

$$j_{em} \left(\frac{2kT_w}{e} + U_D \right) + \frac{j_{em} - j_e + j}{2} U_i = j_e \left(\frac{2kT_e}{e} + U_D \right) + 3.2j \frac{kT_e}{e} + \frac{j_i}{eZ} E.$$

4. Parameters of spots. If a contribution of the heat flux from the arc column to the energy balance of the near-cathode layer is not decisive (which, according to estimates, is a likely case), 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.

The first step has been considered in the preceding section. The third step can be accomplished by means of any of numerical models of an arc column described in the literature. The second step was considered in [7]. In particular, an approximate analytic solution has been obtained for a planar cathode of a transversal dimension much larger than the spot radius. Parameters of cathode spots obtained by means of this approach are shown in Table 1. Here T_* characterizes the surface temperature inside the spot, r_* is the spot radius, $\langle j \rangle$ is the average current density inside the spot, Q is the heat power removed by heat conduction inside the cathode body, T_{e*} is the electron temperature, Z_* is the mean charge number of the ion species, and the last two columns characterize fractions of the ion current and of the current of the counterdiffusing electrons.

In the framework of the present model, parameter T_* as a function of U is governed by the properties of the near-cathode plasma layer and does not depend

U (V)	I (A)	T _* (K)	r _* (mm)	<j> (Am ⁻²)	Q (W)	T _{e*} (K)	Z _*	$\frac{j_{i*}}{j_*}$	$\frac{j_{e*}}{j_*}$
17	971	4450	1.03	2.9·10 ⁸	1876	34827	2.12	0.19	0.13
18	811	4485	0.88	3.3·10 ⁸	1617	37532	2.38	0.18	0.12
19	640	4480	0.77	3.5·10 ⁸	1403	39225	2.55	0.19	0.11
20	493	4450	0.67	3.4·10 ⁸	1230	40150	2.64	0.20	0.10
21	388	4425	0.60	3.4·10 ⁸	1093	41196	2.72	0.21	0.09
22	295	4380	0.54	3.2·10 ⁸	972	41312	2.72	0.23	0.08
23	234	4350	0.49	3.1·10 ⁸	878	41904	2.76	0.24	0.07
24	188	4320	0.45	3.0·10 ⁸	800	42365	2.79	0.25	0.06
25	152	4290	0.41	2.9·10 ⁸	734	42677	2.80	0.27	0.05
26	123	4260	0.38	2.7·10 ⁸	675	42816	2.81	0.28	0.04
27	99	4230	0.35	2.5·10 ⁸	623	42766	2.81	0.30	0.03
12	810	3750	0.92	3.1·10 ⁸	1504	28846	1.64	0.12	0.23
13	447	3760	0.67	3.1·10 ⁸	1111	31155	1.85	0.12	0.21
14	278	3775	0.53	3.1·10 ⁸	881	33691	2.03	0.12	0.19
15	245	3835	0.45	3.8·10 ⁸	763	37017	2.33	0.11	0.18
16	180	3830	0.39	3.8·10 ⁸	652	39197	2.55	0.12	0.17
17	116	3790	0.33	3.3·10 ⁸	557	40689	2.68	0.13	0.16
11.5	711	3810	0.80	3.6·10 ⁸	1326	27432	1.28	0.14	0.18
12.0	584	3865	0.67	4.1·10 ⁸	1134	29030	1.46	0.13	0.17
12.5	460	3890	0.57	4.4·10 ⁸	974	30319	1.61	0.13	0.16
13.0	340	3885	0.49	4.4·10 ⁸	838	31250	1.70	0.13	0.15
13.5	249	3870	0.43	4.3·10 ⁸	729	32043	1.76	0.14	0.14
14.0	182	3860	0.38	4.1·10 ⁸	640	32947	1.83	0.14	0.13
14.5	134	3850	0.34	3.8·10 ⁸	570	33869	1.88	0.15	0.13
15.0	94	3835	0.30	3.3·10 ⁸	509	34696	1.92	0.15	0.12
10.50	905	4080	1.45	1.4·10 ⁸	672	17825	1.00	0.25	0.07
10.75	712	4085	1.26	1.4·10 ⁸	583	18245	1.00	0.25	0.07
11.00	531	4075	1.08	1.4·10 ⁸	503	18385	1.00	0.26	0.06
11.25	421	4080	0.95	1.5·10 ⁸	441	18841	1.00	0.26	0.06
11.50	328	4075	0.83	1.5·10 ⁸	388	19093	1.00	0.27	0.06
11.75	245	4065	0.72	1.5·10 ⁸	337	19226	1.00	0.27	0.05
12.00	193	4065	0.64	1.5·10 ⁸	299	19603	1.00	0.28	0.05
12.25	145	4060	0.56	1.5·10 ⁸	262	19859	1.00	0.28	0.05
12.50	115	4060	0.50	1.5·10 ⁸	235	20255	1.00	0.28	0.05
12.75	87	4055	0.44	1.4·10 ⁸	208	20513	1.00	0.29	0.05

Table 1: Parameters of cathode spots. Uppermost block: tungsten cathode in 1-atm argon plasma. Second block: thoriated-tungsten/argon. Third block: thoriated-tungsten/nitrogen. Lowermost block: zirconium/nitrogen.

on the shape of the cathode, in contrast to the function $T_*(I)$. This allows one to qualitatively analyze the effect of the cathode shape on the spot temperature for non-planar cathodes. Consider, for example, a thoriated-tungsten conical cathode of a variable cone angle, which was studied experimentally [10] in the atmospheric-pressure argon plasma at the arc current 200 A. If the cone angle is close to 180° , the solution obtained for the case of a planar cathode is applicable. As the cone angle decreases, conditions for heat removal from the spot by heat conduction into the cathode body become less favorable. It should be expected that a heat flux density necessary to support a fixed arc current will decrease. The corresponding near-cathode voltage drop, which was initially about 16 V, also decreases. T_* , however, remains nearly constant: while its initial value is 3830 K, the value at $U = 12$ V is 3750 K. The decrease of T_* becomes more pronounced between 11 V and 10 V (from 3700 K to 3500 K), and then T_* again becomes nearly constant.

The experimental results [10] are as follows: The maximum surface temperatures measured for the cone angles from 150° to 24° are almost the same (note that this result looks especially interesting in connection with the fact that a variation of the plasma temperature in the vicinity of the spot in these conditions is rather considerable) and approximately equal to 3500 K; the maximum surface temperature is by some 200 K lower for cone angles of 18° and 12° . Evidently, these results agree qualitatively with the above theoretical considerations, and although the calculated temperature exceeds the measured one by some 300 K, this deviation should be considered as reasonable.

Measurements of the surface temperature of thoriated-tungsten conical cathodes of a fixed cone angle of 60° in the atmospheric-pressure argon plasma at arc currents 100 A, 200 A, and 300 A [10] show that the maximum surface temperature is virtually independent of the arc current and is about 3600 K. The same value is given in [11] for the cone angle of 45° and the current 150 A. The present model explains these results in the following way: It is expected in accordance with the above that the corresponding values of the near-cathode voltage drop are in the range above 11 V, in which T_* is nearly constant.

Measurements of the surface temperature of the conical cathode of pure tungsten of the cone angle of 60° operating with 100 A current in argon at atmospheric pressure [10] show that the maximum surface temperature of the pure tungsten cathode is substantially higher than that of the thoriated-tungsten one. The present model describes this effect. Although the measured value (about 4600 K) is above the range calculated for the case tungsten/argon (4360 ± 130 K), the difference is not large.

A comparative study of arcs in argon and nitrogen at thoriated-tungsten conical cathodes [10] shows that while maximum plasma temperatures are different, the cathode surface temperature profiles are similar. This also agrees with

the present model.

Experiments on planar zirconium cathodes in nitrogen are described in [12, 13]. In the range of I from 80 A to 200 A, measured values of the spot temperature are in the range 3700 A – 4100 K and the ratio Q/I (the so-called volt equivalent of the heat flux) is around 2 V. Theoretical values of T_* and of Q/I for these conditions are 4060 K and 2.4 – 1.5 V, respectively.

5. Acknowledgement. The authors appreciate financial support of JNICT (Portugal), FINEP and FAPESP (Brazil).

References

- [1] B. Ya. Moizhes and V. A. Nemchinskii, *Sov. Phys. - Tech. Phys.* **17**, 793 (1972); **18**, 1460 (1973).
- [2] X. Zhou, J. Heberlein, and E. Pfender, in *Proc. 39th IEEE Holm Conference on Electric Contacts (Pittsburgh, PA, Oct. 1993)*, 229 (1993).
- [3] C. Delalondre and O. Simonin, *Coll. de Physique* **51**, C5-199 (1990).
- [4] P. Zhu, J. J. Lowke, and R. Morrow, *J. Phys. D: Appl. Phys.* **25**, 1221 (1992).
- [5] R. Morrow and J. J. Lowke, *J. Phys. D: Appl. Phys.* **26**, 634 (1993).
- [6] A. Kaddani, C. Delalondre, O. Simonin, H. and Minoo, in *Proc. III European Congress on Thermal Plasma Processes (Aachen, Sept. 1 994)*, 26 (1994).
- [7] M. S. Benilov, *Phys. Rev. E* **48**, 506 (1993); *IEEE Trans. Plasma Sci.* **22**, 73 (1994).
- [8] P. C. Stangeby, *Phys. Fluids* **27**, 682 (1984).
- [9] M. S. Benilov, *J. Phys. D: Appl. Phys.* **28**, 286 (1995).
- [10] J. Haidar and A. J. D. Farmer, *Rev. Sci. Instrum.* **64**, 542 (1993); *J. Phys. D: Appl. Phys.* **26**, 1224 (1993); *J. Phys. D: Appl. Phys.* **27**, 555 (1994).
- [11] M. Ushio, A. Sadek, and F. Matsuda, *Plasma Chemistry and Plasma Processing* **11**, 81 (1991).
- [12] M. F. Zhukov, A. V. Pustogarov, G.-N. B. Dandaron, and A. N. Timoshevsky, *Thermochemical Cathodes* (Novosibirsk, Institute of Thermophysics, 1985).
- [13] V. F. Gordeev and A. V. Pustogarov, *Thermoemission Arc Cathodes* (Moscow, Energoatomizdat, 1988).