A TWO DIMENSIONAL (2D) APPROACH FOR CATHODE SPOT MODELLING

Yuri Vasenin

E.O. Paton Institute
11 Bozhenko St., Kiev 03680, UKRAINE

http://www.plasma.kiev.ua
E–mail: PLASMINT@YAHOO.COM

1. Introduction

The nonstationary cathode spot has a complex of fragments when the electric current exceeds of some value. Its chaotical movement over the surface may be guided by the external transverse magnetic field to the anti–Amperian (retrograde) direction. The inner structure of the cathode spot play substantial role in all these phenomena [**1**, **2**, **3**], and its behaviour must be described at least in a two–dimensional models.

2.Equations

2.1 Non–stationary heat conduction with cylindrical symmetry

Models with two-dimensional heat conduction developed for cathodes with thermionic emission can yield more details also for the spot processes. Such models use boundary conditions for the energy flow Q_s from the near-cathode plasma to the cathode surface and the current density on the surface J_c. For the cathode spot on copper these parameters are available from [4], so it is possible to use a standard set of equations.
In cylindrical symmetry the equation for non–stationary heat conduction reads

$$\rho c \frac{\partial T}{\partial t} = \lambda \frac{1}{R} \frac{\partial}{\partial R}\left(R \frac{\partial T}{\partial R} \right) + \lambda \frac{\partial^2 T}{\partial Z^2}, \tag{1}$$

with the initial and the boundary conditions for the energy transition trough the surface (Z=0), into the spot center (R=0) and into the metal bulk are

$$\begin{gathered} T\big|_{t=0} = T_0, \quad T\big|_{\substack{R\to\infty \\ Z\to-\infty}} = T_0, \quad T_c = T\big|_{Z=0}, \\ -\lambda \frac{\partial T_c}{\partial Z} = Q_s(T_c, U_c), \quad -\lambda \frac{\partial T}{\partial R}\bigg|_{R=0} = 0. \end{gathered} \tag{2}$$

The current is determined by

$$I_a = I(R_{ex}), \quad I(R) = 2\pi \int_{R_{in}}^{R} J_c(T_c(r), U_c(r)) \cdot r dr \tag{3}$$

$R_{in} \geq 0$ being the radius of the inner region with a current density $J_c \geq 10$ A/cm^2 and $Q_s \geq 0$; R_{ex} is the outer radius of the spot region at which $J_c \leq 10$ A/cm^2 and $Q_s \leq 0$.

2.2 Hall effect in the positive space-charge layer

With the above set of equations there occurs a singularity at the spot centre in dependence on (U_c,T_c) energy flow, and current density at the surface. This is the numerical analogue to the well known 'thermal runaway' [5]. In the 1D-description such runaway was avoided by

Proceedings of 24th International Conference on Phenomena in Ionized Gases (**ICPIG**),
Warsaw, Poland, July 1999, v.2, pp.179-180.

taking into account the displacement of the emitting surface, allowing extremely high temperatures only at ignition. In our 2D-model the surface displacement is not taken into account, so it is necessary to search for other possibilities to avoid thermal runaway. As it may be seen in [4], at high temperatures the energy flow to the cathode surface steeply depends on the cathode fall U_c, thus its variation markedly influences the energy balance.
The simplest reason for a radial variation U_c is the Hall effect in the positive space charge sheath due to the self-generated magnetic field of the spot current. The theory of magnetised plasma–sheath transition region presented in [6]. Its proper using will dramatically increase the complexity of the self–consistent calculations. The simple evaluation of the possible effect on the cathode spot structure presented below.
The transverse magnetic field displaces the negative space charge of the emitted electrons, accelerated by the cathode fall, in the Amperian direction (towards the spot centre), until the increasing electric field (Hall field) of the positive charge at the spot border compensates the Lorentz force. For the radial component of the electric field $F_r = -\partial U/\partial r$ we put $0 = -\mathrm{e}F_r - \mathrm{e}V_e H/c$, where V_e is the velocity of the emitted electrons at the edge of the positive space charge sheath, c is velocity of light, magnetic field $H(r) = 0.2 \cdot I(r)/r$ (current in [A], radius in [cm], H in [Gauss]). So the potential has a radial distribution over the cathode surface with the minimum U_{co} at the centre (or at R_{in}) and the maximum at the outer spot radius R_{ex}:

$$U_c(R) = U_{co} + \frac{1}{c}\int_{R_{in}}^{R} V_e(U_c(r)) \cdot g(r) \cdot H(r)dr, \tag{4}$$

where $g = J_e/J_c$ is the ratio of the electron component to the total current.
The analysis for the Hall electric field caused by an external magnetic field in the neighbourhood plasma of the spot was carried out at [7]. However, in the present case the velocities of the emitted electrons are much higher than those of the plasma electrons, so the Hall effect is greater. The other origin of the spot structure may be the back flow of the plasma electrons [8].

3. Results

2D model gives new possibilities for the spot description at long term operation: Formation of ring structures and displacement of the energy source Q_s towards the external radius due to a redistribution of the cathode fall over the surface. This causes the temperature maximum begins to move over the surface and $T_{\max}$ to be situated near the border of the spot.
fig. a shows radial and depth distributions of the temperature at different times. Obviously, there exists a critical current I^* up to which the thermal diffusion into the cathode bulk is able to control the spot processes. The distribution of U_c over the spot surface can be seen also in fig. a in more detail.
Because the 2D model is based on the relation of Q_s to the local values of the surface temperature T_c and the cathode fall U_c, it may be used with better accuracy for the description of the quasi–stationary spot.
The hollow temperature profile, the internal and external radii R_{in} , R_{ex} at different arc

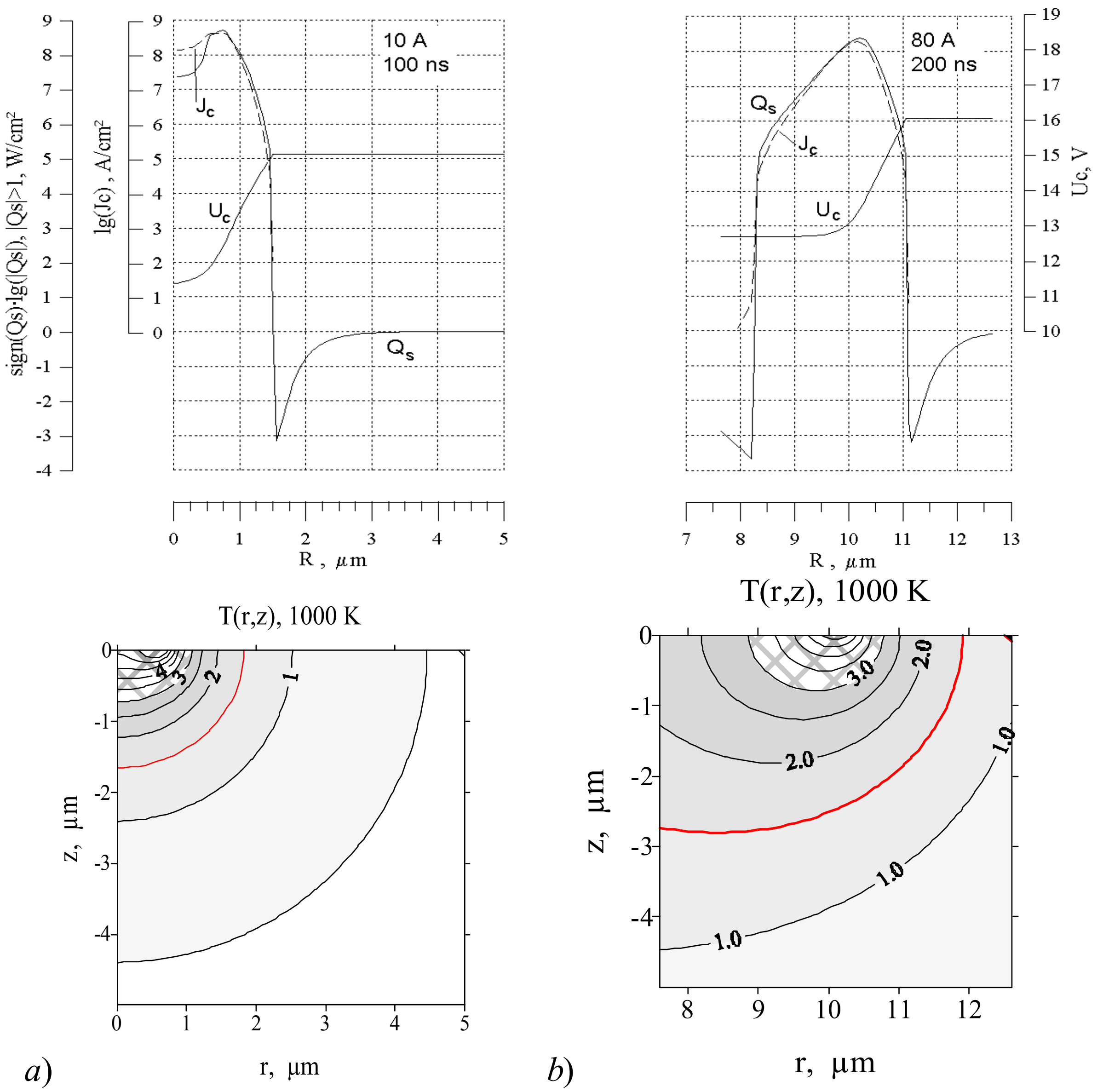

Fig. A. The distributions of energy flow Q_s, current density J_c, and cathode fall U_c over the spot surface (a), and the temperature distribution T(r,z,t) in the cathode bulk (b) for different currents and times. a – I_a=10 A, *t* =100 ns ; *b –* I_a=80 A, *t*=200 ns .

currents is illustrated in fig. b. It is interesting to note that below a critical current $I_a<I^*$ this hollow profile is absent. The calculated value I^*≈30A has a qualitative meaning and may be changed with additional treatment (for example, in the case of a combined 1D+2D model).
The temperature inside the valley may grow with time for I_a<45A, and decrease for I_a>50A. When it surpasses the switch-on temperature (~2200K for copper, depending on U_c), the hollow structure disappears, as it does at I^*≈30A in fig. b*b*.
The calculated velocity $V_b = R_{ex}/t$ are dependent on the current, contrary to the case of the 1D model and may rise up to 800 m/s, decreasing with time.

4. Summary

The Hall field in the space-charge zone caused by the self-generated magnetic field leads to a hollow profile of the surface temperature. The hollow structure of the temperature

Proceedings of 24th International Conference on Phenomena in Ionized Gases (**ICPIG**),
Warsaw, Poland, July 1999, v.2, pp.179-180.

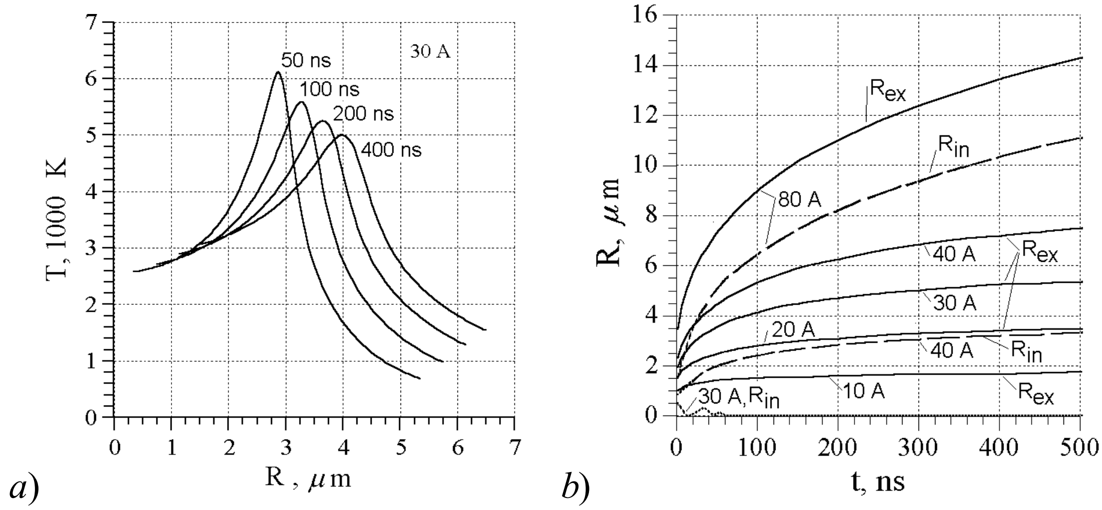

Fig. B. The temperature distribution over the surface, relative to the spot center (*a*) *and the time dependence of radii* R_{ex} *and* R_{in} *for different spot currents* (*b*).

distribution promises to provide a key for the understanding of basic spot phenomena, viz. formation of fragments, spot splitting, and spot movement. Fragment formation and spot splitting become probable above the critical current I^* (30 A for Cu), transforming the ring structure into a group of circles. Asymmetric expansion of the spot border may lead to movement. In particular, the asymmetry may be caused by an external magnetic field, so there is hope to explain the retrograde direction of the movement.

5. Acknowledgments

The author is indebted and gratefully acknowledges to Professor B. Jüttner for valuable help and support of the work.
This work was supported by the German Ministry of Sciences BMBF, grant 13N6616.

6. References

[1] B. Jüttner, V.F. Puchkarev: in Handbook of Vacuum Arc Science and Technology, ed. by R.L. Boxman, P.J. Martin and D.M. Sanders, NOYES Publications Park Ridge, New Jersey, U.S.A. (1995) 73.
[2] I.G. Kesaev: Cathode Processes in Electric Arcs. Moscow:Nauka (1968) (in Russian).
[3] L.P. Harris: in Vacuum Arcs. Theory and Applications., ed. by J.M. Lafferty. J. Wiley & Sons, Inc., U.S.A. (1982).
[4] Yu. Vasenin : Proc. of 18th ISDEIV, Eindhoven, The Netherlands (1998) 341.
[5] E. Hantzsche: IEEE Trans. Plasma Sci., PS-11, (1983) 115.
[6] K.–U. Rieman: J.Phys.D: Appl.Phys., 24 (1991) 493.
[7] B.Ya. Moizhes and V.A. Nemchinsky: J.Phys.D: Appl. Phys, 24 (1991) 2014.
[8] S.A. Barengolts, E.A. Litvinov, E.Yu. Sadovskaya, and D.L. Shmelev: Zh. Tekh. Fiz, 68 (1998) 60.

Proceedings of 24th International Conference on Phenomena in Ionized Gases (**ICPIG**),
Warsaw, Poland, July 1999, v.2, pp.179-180.