Detailed Numerical Simulation of Cathode Spots in High-Current Vacuum Arcs

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***Abstract*- A detailed numerical model of cathode spots in high-current vacuum arcs is given. The model provides a complete description of all phases of life of an individual spot taking into account the presence of metal vapor left over from a previous explosion, the interaction of the vaporized plasma from the cathode spot with the cathode surface, and Joule heat generation in the cathode body. Melting and motion of molten metal due to Lorentz force are also accounted for, together with surface tension effects and the pressure exerted by the plasma over the cathode surface. First results are presented and analyzed for copper cathodes with a protrusion and planar cathodes. Emphasis is given to the investigation of the effect of the vaporized plasma and of hydrodynamic processes. No thermal runaway is observed.**

I. INTRODUCTION

A variety of approaches used for the modeling of cathode spots in vacuum arcs can be found in the literature. In particular, there are space-resolved descriptions of spot initiation and development based on numerical solution of 2-D partial differential equations, e.g. see [1-5]. Some of these authors also observe the appearance of thermal runaway below the cathode surface in their numerical solutions. A possible result of this instability is a microexplosion of a cathode protrusion, accompanied by explosive electron emission (ecton) [6, 7].

Most of the available models consider only the thermal development of the cathode spot, neglecting hydrodynamic processes. Recent works by Mesyats and coworkers [5, 8] point to the importance of these processes in the evolution of the molten cathode surface and in the self-sustainment of the vacuum arc discharge.

It is in the sequence of these previous works that a detailed numerical model of cathode spots in high-current vacuum arcs has been developed. The model aims to provide a complete description of all phases of life of an individual spot taking into account the presence of metal vapor left over from a previous explosion, the interaction of the vaporized plasma from the cathode spot with the cathode surface, and Joule heat generation in the cathode body. Melting, surface tension effects, motion of molten metal due to Lorentz force and under the action of the pressure exerted by the plasma over the cathode surface are also accounted for.

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II. THE MODEL

The detailed numerical model presented builds upon a self-consistent space-resolved model of stationary cathode spots in vacuum arcs, developed in the course of previous investigations [4]. The model is axially symmetric, the equations are solved in a cylindrical domain. The temperature T and electric potential φ distributions are calculated in the cathode body by means of solving the time-dependent heat conduction equation, written with account of convection and Joule heat generation in the body of the electrode, and the equation of current continuity supplemented with Ohm's law. The definition of material properties and boundary conditions for the temperature and electric potential far away from the spot can be found in [4]. Boundary conditions on the cathode surface are written in terms of densities of the energy flux, $q = q(T_w, U)$, and electric current, $j = j(T_w, U)$ from the plasma to the surface, computed in advance as functions of the local cathode surface temperature T_w and the near-cathode voltage drop U. Functions q and j are evaluated using the model of near-cathode plasma layers in vacuum arcs, based on a numerical simulation of near-cathode space-charge sheath with ionization of atoms emitted by the cathode surface ([4] and references therein).

In addition, the contribution of metal vapor left over from a previous explosion on the densities of energy flux and electric current from the plasma to the cathode surface is taken into account. Characteristic values of ion density n_i, electron temperature T_e, and ion charge Z are assumed for the left-over plasma [7]. Assuming that the cold ions enter the near-cathode space-sheath edge with Bohm's velocity and are accelerated by a near-cathode voltage U, the densities of ion current j_i and energy flux q_i from the plasma to the cathode surface can be estimated as:

$$j_i = Zen_i(kT_e/m_i)^{1/2}, \quad q_i = j_i U, \tag{1}$$

where e is the electron charge, m_i the ion mass and k the Boltzmann constant.

The net densities of energy flux and electric current are written in the form

$$q = q(T_w, U) + q_i f(r) f(t), \; j = j(T_w, U) + j_i f(r) f(t), \quad (2)$$

where $f(r)$ and $f(t)$ are functions specifying the spatial and temporal distribution of the left-over plasma.

The magnetic field distribution **B** generated inside the cathode body is calculated by means of Ampère's law. For all boundaries a magnetic insulation boundary condition is set.

The motion of the molten metal is governed by the time-dependent Navier-Stokes equations for incompressible fluids, accounting for surface tension effects and the Lorentz force that contributes to the motion of the fluid. A no-slip boundary condition is used for all external boundaries. On the cathode surface, forces due to surface tension and pressure P exerted by the plasma are introduced as boundary conditions. The plasma pressure includes contributions from both the vaporized plasma from the cathode spot (computed in advance) and the left-over plasma (computed from q_i), introduced in the same form as (2).

The problem is numerically solved by means of the commercial software COMSOL Multiphysics, with implementations of the enthalpy-porosity method for modeling the solid-liquid phase transition, and of the level-set method for tracking the deformation of the molten cathode surface.

III. RESULTS AND DISCUSSION

Calculations were performed for cathodes with a Gaussian-shaped microprotrusion, 1 μm in height and 1 μm in base radius, and for planar cathodes. The cathode material in both cases is copper. Unless specified otherwise, simulations were performed with a time of action of the left-over metal vapor on the cathode surface of τ = 100 ns, and a corresponding action radius of 5 μm. Values of $n_i = 10^{26}$ m^{-3}, $T_e = 2$ eV, Z = 2, $U = 20$ V have been assumed.

First results are presented depicting the initiation and development of the cathode spot, and the evolution of the molten cathode surface, resulting in the formation of craters under the action of the plasma pressure. Results of modeling without account of motion of the molten metal, similar to those presented in the referenced literature, are used as a benchmark.

A. Cathode with a microprotrusion

Fig. 1 shows the results of simulation for a cathode with a microprotrusion. As a first important result, the model reveals the destruction of the protrusion due to melting and the initial stages of the formation of a crater within ~22 ns (Fig. 1a). The crater formed is shallow, less than 0.5 μm deep. The maximum temperature T_{max} in the cathode does not exceed ~4700 K throughout the calculation (line HD & V in Fig. 1d). Thus, thermal runaway has not developed. Vaporization and electron emission cooling are dependent on local surface temperature and contribute appreciably to the cathode surface energy balance at such temperatures.

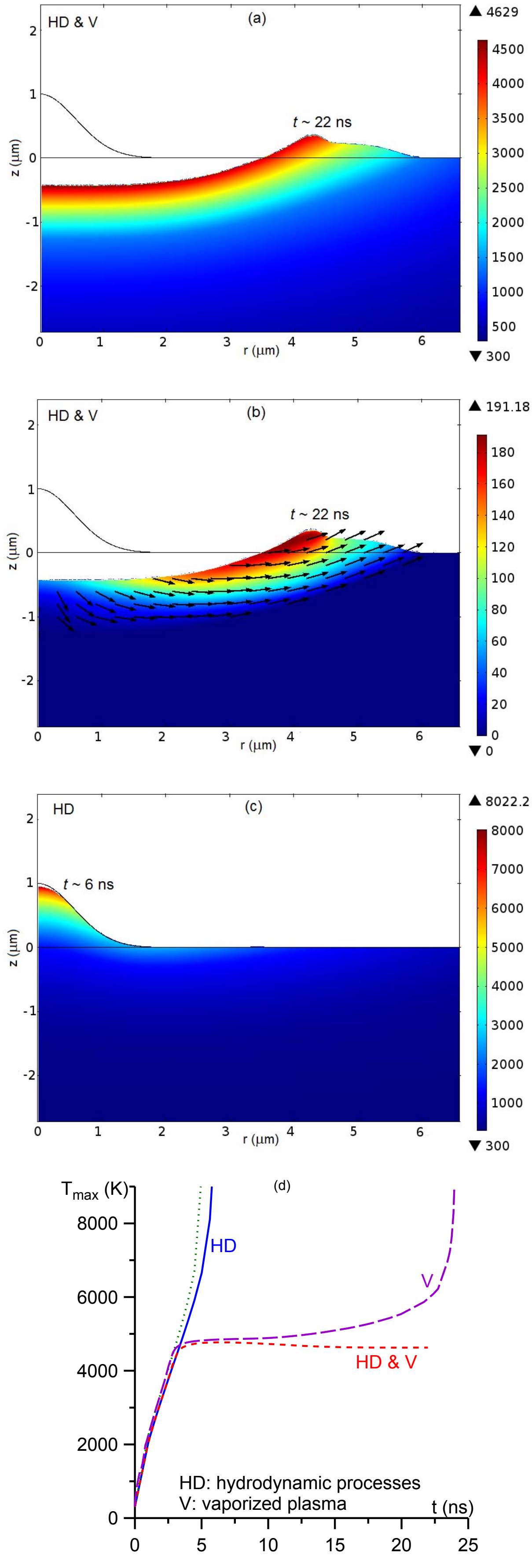

Fig. 1. Results of simulation for cathode with a microprotrusion. (a), (c): the bar in K. (b): arrows are indicative of direction of flow; the bar in m/s.

Furthermore, the transport of heat in the molten metal is quite significant owing to high fluid velocities: the high plasma pressure (P ~2×10^8 Pa) accelerates the molten metal to velocities of ~190 m/s (Fig. 1b), transporting heat from the center of the crater toward the periphery. Both processes will lead to the cooling and eventual solidification of the formed crater, once the left-over metal vapor no longer acts on the cathode surface.

The second relevant result is presented in Fig. 1c and complemented by line HD in Fig. 1d, which show quite clearly the effect the absence of vaporization and electron emission have on the evolution of the system. A rapid overheating of the surface of the protrusion is observed (the critical temperature T_{crit} is reached in ~6 ns), with no appreciable deformation of the molten surface or motion of the liquid metal. On such short time scales, hydrodynamic processes do not have time to develop and heat dissipation into the bulk cathode is ineffective. A comparison to the dotted line in Fig. 1d, which gives the temporal evolution of T_{max} in the case of the model without motion of molten metal or vaporized plasma, shows an almost identical result.

Line HD in Fig. 1d, shows that hydrodynamic processes have a weak cooling effect on the system. The vaporized plasma contributes more strongly as a cooling mechanism, but is still not sufficient to prevent thermal runaway development below the cathode surface (line V in Fig. 1d). Accounting for both cooling mechanisms in the model prevents the appearance of this thermal instability (line HD & V in Fig. 1d). In the referenced works, only Schmoll [1] gives a model including both the vaporized plasma and hydrodynamic processes, and the results also reveal no development of thermal runaway.

B. *Planar cathode*

Fig. 2 and 3 present the results of simulation for a planar cathode. The formation of a crater occurs up to ~28 ns, where, again, the temperature does not exceed ~4700 K throughout the calculation (Fig. 2a and line HD & V in Fig. 2c). Similarly to the result described in section A, vaporization and electron emission cooling contribute appreciably to the cathode surface energy balance and the molten metal, accelerated to velocities of ~220 m/s, transports heat from the center of the crater toward the periphery (Fig. 2b). Thus, thermal runaway has not been computed and should not develop for $t > 28$ ns.

The results for the cathode with a microprotrusion reveal that, in the absence of vaporized plasma, hydrodynamic processes do not have time to develop and there is only minimal deformation of the protrusion before T_{crit} is reached in a few nanoseconds. The behavior computed for the case of the planar cathode is noticeably different. Heating on a planar cathode occurs on longer timescales, which allows sufficient time for hydrodynamic processes to develop and for a crater to form even when the vaporized plasma is neglected (Fig. 3a, 3b). Comparing the temporal evolution of T_{max} of this calculation (line HD in Fig. 2c) to the analogous situation where these processes are neglected (dotted line in Fig. 2c; Fig. 3c) shows that the motion of molten metal has a more prominent role as a cooling mechanism in the planar cathode geometry, than in the cathode with a microprotrusion (cf. Fig. 1d).

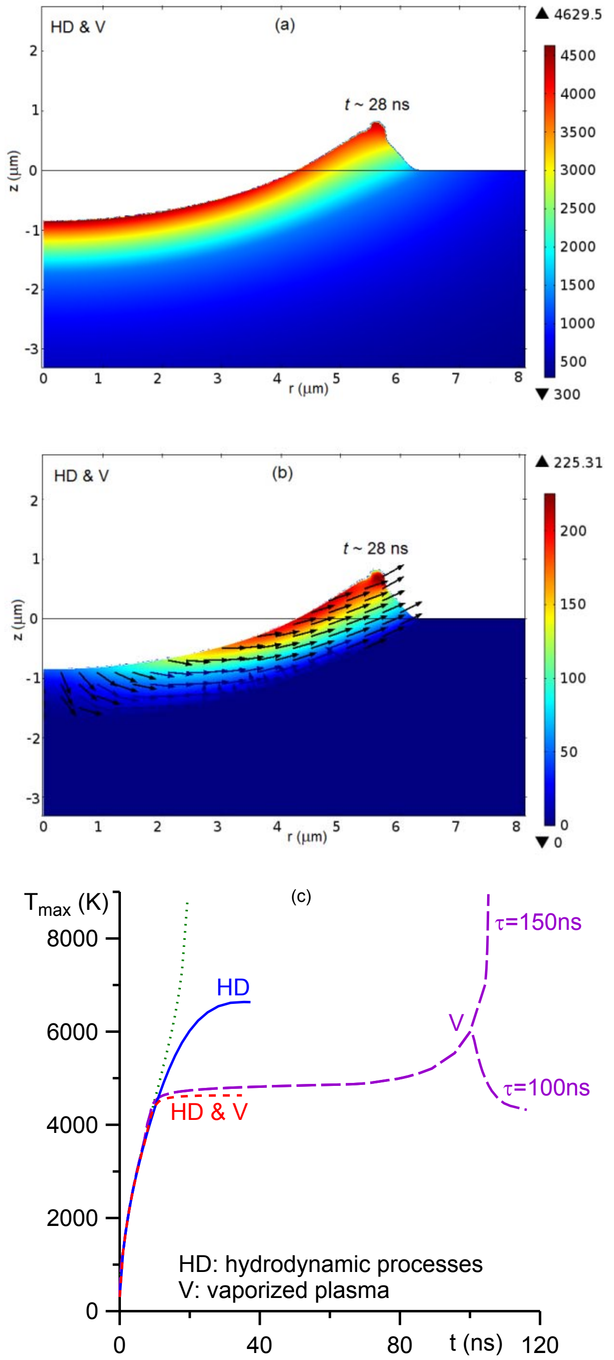

Fig. 2. Results of simulation for planar cathode. (a): the bar in K. (b): arrows are indicative of direction of flow; the bar in m/s.

The planar geometry is more favorable for the development of hydrodynamic processes. Vaporization and electron emission still have a more pronounced cooling effect, but are still insufficient to prevent

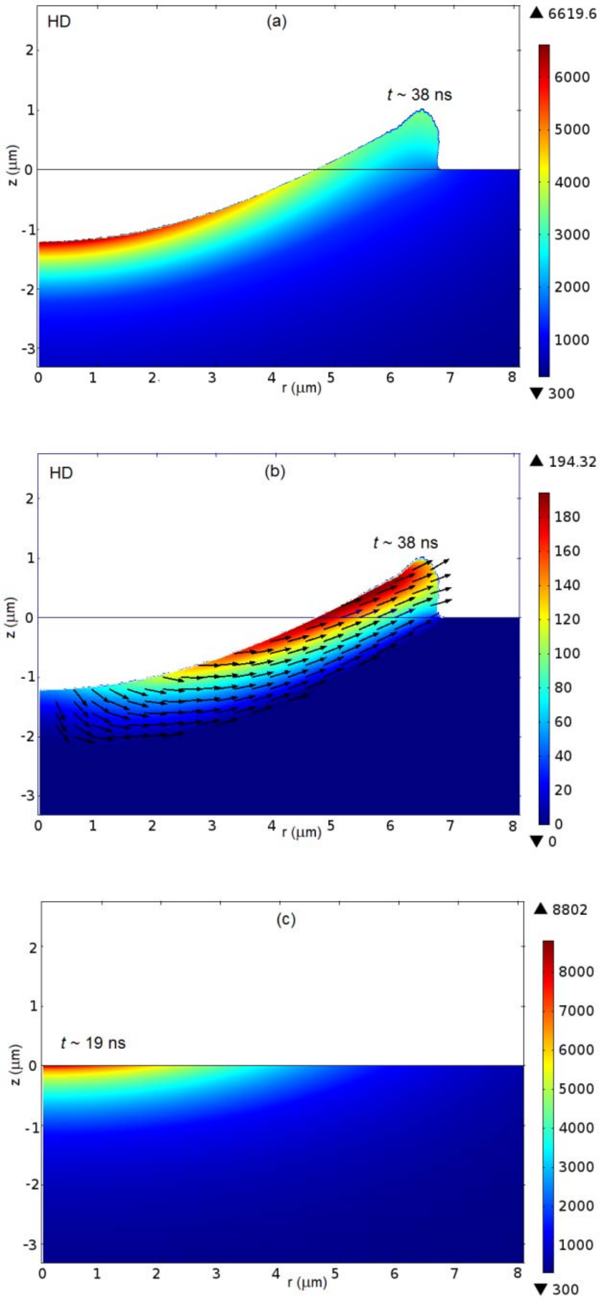

Fig. 3. Results of simulation for planar cathode, without account of vaporized plasma. (a), (c): the bar in K. (b): arrows are indicative of direction of flow; the bar in m/s.

thermal runaway, unless the action of the left-over metal vapor stops (line V in Fig. 2c). As for the case of the cathode with a microprotrusion, accounting for both cooling mechanisms also prevents the appearance thermal runaway in the planar cathode (line HD &V in Fig. 2c).

IV. CONCLUDING REMARKS

A detailed numerical model of cathode spots in high-current vacuum arcs is given. The model described the full cycle of life of a spot. First results are reported for copper cathodes with a microprotrusion or with a planar surface.

The Lorentz force generated in the cathode body is several orders of magnitude lower than the force exerted by the plasma pressure on the cathode surface. Thus, the plasma pressure is the prevailing mechanism for acceleration of the molten metal toward the periphery of the spot. Vaporization and/or electron emission, as well as the convective heat transfer, are dominant mechanisms of cooling of the cathode surface.

The development of a spot leads to formation of a crater on the cathode surface. However, no microexplosion (thermal runaway) is observed, provided both cooling mechanisms are taken into account. Instead, the cathode surface is cooled down and eventually solidifies. This happens even under the continual action of the left-over metal vapor. Note that this scenario conforms to the numerical results [9], given that the present numerical results refer to a fixed near-cathode voltage drop.

The above results seem to be in stark contrast with the reigning paradigm of explosive emission. The likely reason is the neglect of one or both above-mentioned cooling mechanisms (vaporization and/or electron emission and convective heat transfer) in the preceding works. On the other hand, no thermal runaway was observed in numerical simulations [1], which was the only preceding work in which both cooling mechanisms have been taken into account.

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