Possible explanation of the mechanism of cathode spot motion

A. V. Zharinov and Yu. V. Sanochkin
V. I. Lenin All Union Electrical Engineering Institute

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A thermal capillary mechanism for cathode spot motion is proposed. The velocity of the spot is determined and the convection pattern is examined.

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The phenomenon of continuous chaotic motion of cathode spots[1,2] has never been explained. In addition, in the literature on low-pressure a cold-cathode arcs there is a tendency to relate the dynamics of cathode spots only to process in the plasma column and the near-cathode layer. It appears, however, that the motion of a cathode is due primarily to processes in the liquid-metal layer beneath the spot. We shall demonstrate this. We shall examine a single spot with a single emitting cell (EC), whose dimensions, are small compared with the diameter of the spot $2l$. The dynamics of the spot are determined by the motion of the liquid particle (EC), which is heated to emission temperature T_0 and which communicates the electric current. The temperature of the surface of the liquid changes over a distance $\sim l$ from T_0 to T_1, where T_1 is close to the temperature of the cathode (in the case of a liquid cathode) or is equal to the melting temperature of the metal (in the case of a solid cathode). The temperature drop indicated $\Delta T = T_0 - T_1$ can attain magnitudes of $\sim 1000°$. Therefore, the tangential stress on the free surface, because of the gradient of the coefficient of surface tension $\nabla\sigma$, can also be large. For this reason, thermal capillary convection develops in the fluid layer.[3] The velocity of the spots is very high $v_0 \sim 10 - 10^4$ cm/s. The Reynolds number $\mathrm{Re} = v_0 l/\nu$ for spot sizes of $l \sim 10^{-2} - 10^{-4}$ cm is high. This means that the effect of viscosity is manifested in a thin near-surface layer, i.e., the thickness of the fluid layer h set into motion by the capillary force turns out to be small compared to l. The return flow can encompass a thicker layer. The explanation of high velocities v_0 with a large delay in cathode heating presented the greatest difficulties.[1] This difficulty can be overcome if the dominant mechanism for heat transfer is convection at sufficiently high velocities. An estimate of the Peclet number $\mathrm{Pe} = \nu\mathrm{Re}/\chi \gg 1$ indicates the fact that convective heat transfer plays the main role in the phenomenon being examined.

Let us assume, for simplicity, that the surface of the liquid metal in the spot remains flat and let us examine first the case in which EC (T_0) is situated exactly at the center of a round spot (Fig. 1). The symmetrical curves with the arrows indicate the stream lines in the section of the spot in the xy plane and the lower line indicates the isotherm T_1. The condition

$$\nu\rho\frac{\partial v_x}{\partial y} = \frac{d\sigma}{dx} = -a\frac{\partial T}{dx}, \quad \left(a = -\frac{\partial\sigma}{dT} = \text{const}\right)$$

is satisfied on the free surface ($y = 0$), and it may be assumed that $\partial T/\partial y = 0$ far from T_0. In order to find the flow velocity and the relation between h and l, it is necessary to solve the complete system of equations of free convection with the boundary conditions indicated. (Convection due to buoyancy is not important in this case.) The solution in the region $x \gtrsim h$, obtained in the boundary layer approximation for a flat-spot model when the total fluid flux in any cross section is equal to 0 and $h = $ const, has the form

$$T = T_1 + (T_0 - T_1)(1 - x/l)^2\,\theta(y/h), \quad v_x = v_k(1 - x/l)\,u(y/h), \tag{1}$$

where

$$v_k = f(P)\left(\frac{a\Delta T}{\nu\rho}\right)^{2/3}\left(\frac{\chi}{2l}\right)^{1/3} \tag{2}$$

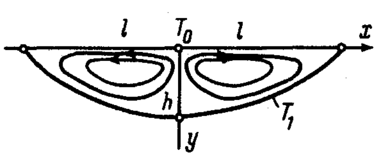

FIG. 1.

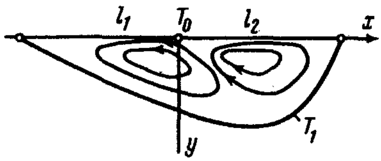

FIG. 2.

is the maximum velocity of thermal capillary convection on the free surface. θ and u are dimensionless functions, which determine the distribution of T and v_x as a function of y. The thickness of the convection cell is related to the dimensions of the spot by the relation

$$h = g(P)\left(\frac{\rho\nu\chi}{a\Delta T}\right)^{1/3}(2l)^{2/3}. \tag{3}$$

The functions f and g of the Prandtl number in (2) and (3) for fused metals turn out to be ~ 1. According to (3), for conditions in the spot, $h \ll l$, as assumed, i.e., in the case of a hard cathode, for example, the depth of the fluid bath can be less than l. The nature of the fluid motion remains as before, if h varies little as a function of x. Thus, h in (3) may be understood as some average quantity. Thus, the temperature distribution in the spot turns out to be parabolic, while the convection velocity decreases linearly.

For a strictly symmetrical positioning (Fig. 1), a fluid particle T_0 is not subject to forces and the spot remains at rest. However, this state is absolutely unstable. Any random displacement of the point T_0 or deformation in the shape of the spot is sufficient to cause the pattern to become asymmetrical (Fig. 2). On the left side of the convective cell ($l_1 < l_2$), the temperature gradient and, therefore, the velocity v_k turn out to be greater than in the cell on the right side. The velocity head of the left vortex is greater than for the right vortex, so that the latter is partially pushed out from under the particle T_0. Thus, in addition to the resulting surface force on the EC oriented to the left, a component of the lifting force of the rising flow acts in the same direction and the center of gravity of the particle begins to move with velocity $v_0 \geqslant (v_{k_1} - v_{k_2})/2$. In contrast to the symmetrical state, the motion is stable, since the average depth of the heated (melted) zone in front of the moving spot h_1 is always much less than the thickness of the liquid layer h_2 behind the spot and, therefore, according to (3), the condition for motion $l_1 < l_2$ is automatically maintained. Thus,

$$v_0 \cong \frac{1}{2} f(P)\sqrt{\frac{a\Delta T\chi}{\rho\nu h_1}}\left(1-\sqrt{h_1/h_2}\right). \tag{4}$$

The ratio h_1/h_2 depends on v_0. A calculation of the slope of the isotherm T_1 as a function of v_0 shows that the last factor in (4) is ~ 1 over a wide range of conditions in the spot.

From an estimate of the convection velocities (2) and motion of the spot (4) it follows that they can attain the observed values $10^3 - 10^4$ cm/s. For mercury, setting $\nu \sim 0.0001$ cm^2/s, $\chi \sim 0.02$ cm^2/s, $a = 0.5$ dynes/cm deg and $2l = 10^{-3} - 10^{-4}$ cm, we find $v_0 \sim (20\text{–}40)\cdot(\Delta T)^{2/3}$ or $v_0 \sim (4\times 10^2 - 10^3)$ cm/s with $\Delta T = 100°$. Uniform rectilinear motion of the cathode spot with velocity v_0 along the surface of a real material is impossible. The presence of impurities, inhomogeneities, and irregularities on the cathode surface make the motion of the spot a random process, similar to the motion of a Brownian particle. This is even more obvious if we recall that a real spot always has a complex shape and it can contain several moving EC. Within the scope of the model proposed, the phenomenon of the fixation of spot motion along the wetting curve of a solid metal and another liquid metal becomes understandable. The pattern of laminar convection in a single spot with a single EC examined above can become unstable under certain conditions. It appears that spot and EC decomposition and division are related to this phenomenon.

[1]V. L. Granovskiĭ, Elektricheskiĭ tok v gaze. Ustanovivshiĭsya tok (Electrical Current in Gases. Steady-State Current), Moscow, 1971, Chap. X.

[2]I. G. Kesaev, Katodnye protsessy élektricheskoĭ dugi (Cathodic Processes in An Electric Arc), Moscow, 1968.

[3]V. G. Levich, Fiziko-khimicheskaya gidrodinamika (Physicochemical Hydrodynamics), Moscow, 1959, Sec. 68.

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