ARC THERMAL PROCESSES AT FILM CATHODES

G. S. Belkin

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Computer solution is presented for the axially symmetric heating of a film cathode; the results are used to examine the trace of the cathode spot on the film, the proportion of evaporation energy in the energy balance, etc. The effects are considered for the size of the heat source in relation to the heat conditions in the cathode spot.

Film cathodes are effective in research on cathode phenomena in electric arcs [1]; the marks left by the spot enable one to estimate the current density, the product of the ion accommodation coefficient α and the ionic fraction f of the current, etc. The values given [1] for f (about 0.05) for copper films represent a lower limit and correspond only to one of the possible heating conditions, namely that where evaporation is absent. There was in [1] no discussion of conditions accompanied by extensive metal evaporation, which involves large amounts of energy absorbed per unit volume of molten metal. In that case one obtains values of f much larger than 0.05. In some experiments with bulk cathodes [2, 3], the erosion could be explained in terms of such a small ionic component of the current.

A thin film cathode may become very highly heated by a spot, and there may be vigorous evaporation of the metal; a given removal of energy by thermal conduction may correspond to different values of energy dissipated at the surface and energy consumed in evaporation, i.e., the deposit of energy and $f\alpha$ do not define unambiguously the width of the molten spot. We consider here what heat fluxes and radii of the sources in the cathode spot on a copper film are such as to give rise to rapid evaporation, and to what extent the deposited energy may exceed that removed by thermal conduction, i.e., how far $f\alpha$ can exceed the value defined in [1].

Here we present computer results on the growth of the track in a film cathode and the variation in the proportion of energy consumed in evaporation as the spot parameters vary.

The solution concerns the heating of a thin film on an insulating substrate (Fig. 1), which takes into account evaporation of the metal, motion of the molten front into the film, and the temperature dependence of the thermophysical parameters of the metal. The heat source is uniformly distributed in an area of radius R_0. The film thicknesses were 1.2, 1.8 and 6 μm, which are somewhat larger than the thicknesses used in [1]; however, although evaporation was more important for the thicker films, the energy used up in evaporation was even larger for the thinner ones.

The following is [4] the equation of thermal conduction in cylindrical coordinates for this case:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right). \tag{1}$$

This equation is to be solved subject to the following boundary conditions:

the equation of flux balance at the surface of the metal with

$$0 \leqslant r \leqslant R_0$$

$$q_B = -\lambda \frac{\partial T}{\partial z}\Big|_{z=\eta} + q_{\text{eva}}(T|_{z=\eta}), \tag{2}$$

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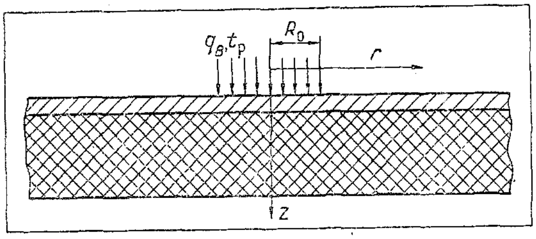

Fig. 1. Calculation of film cathode heating.

with

$$r > R_0$$

$$0 = -\lambda \left.\frac{\partial T}{\partial z}\right|_{z=\eta} + q_{\text{eva}}(T|_{z=\eta}), \tag{3}$$

with

$$0 \leqslant r < \infty$$

$$0 = \left.\frac{\partial T}{\partial z}\right|_{z=D}; \tag{4}$$

the equation for the motion of evaporation front

$$\gamma \frac{d\eta}{dt} = \mu (T|_{z=\eta}). \tag{5}$$

Solution of (1)-(5) allows one to determine the temperature distribution in the film at different instants for various heat sources.

Figure 2 shows the change in the cathode spot for films of copper of thickness 1.2, 1.8, and 6 μm; the melted depth is dependent on r, which is due to the propagation of heat along the r coordinate, which causes the diameter of the molten spot to exceed that of the heat source. For instance, with a flux of $3 \cdot 10$ cal/sec-cm^2 there was a ratio of melted diameter to source diameter of 1.35 at a time of $1.22 \cdot 10^{-6}$ sec, which means that a substantial error can arise in determining the current density from the size of the track because this does not coincide with the size of the heat source.

Equations (1)-(5) do not take into account the motion of the heat spot over the surface of the film; but the results for a fixed heat source can be used for an approximate evaluation of the heating conditions in the moving spot. We consider a spot moving with velocity v as spending a time $2R_0/v$ at a given point, while the heating of the metal in time t_s corresponds to the condition in the spot moving with a speed v_{calc} equal to $2R_0/t_s$.

Table 1 gives the surface temperatures, evaporation fluxes, and v_{calc} corresponding to various conditions.

The speed of the cathode decreases as the film becomes thicker [1], and it was $2.4 \cdot 10^3$ cm/sec for a film 0.66 μm thick. The v_{calc} for some heating conditions are close to the observed ones [1], while in other cases the former substantially exceed the latter, and correspondingly the times of action in the experiment may have greatly exceeded the t_s stated in the table, which means that a high proportion of energy was consumed in evaporation under certain conditions, in which case one needs to take into account the evaporation energy in calculating the depositing energy and $f\alpha$ [1]. Allowance for the evaporation causes $f\alpha$ to increase substantially over the values given in [1].

The following conclusions can be drawn from the tabulated results. The heat flux at which evaporation becomes appreciable in the energy balance is dependent on the radius of the heat source; if the latter is 10^{-4} cm and the spot speed is about 10^3 cm/sec, evaporation becomes substantial only for heat fluxes greater than $3 \cdot 10^7$ cal/cm$^2 \cdot$sec.

TABLE 1. Evaporation Energy as a Function of Cathode Spot Parameters

q_B, cal /cm$^2 \cdot$sec	Film thickness, μm	R_0, cm	$T(0,0)$, °K	t_s, nsec	q_{eva}/q_B	$v_{\text{calc}} = 2R_0/t_s$, cm/sec
$3 \cdot 10^6$	6	10^{-3}	3280	720	9%	$2{,}78 \cdot 10^3$
			3770	1420	40%	$1{,}41 \cdot 10^3$
		10^{-2}	4020	1260	70%	$1{,}59 \cdot 10^4$
10^7	1,8	10^{-4}	3530	430	6%	$0{,}465 \cdot 10^3$
		10^{-3}	4170	67	30%	$3 \cdot 10^4$
			4350	100	50%	$2 \cdot 10^4$
		10^{-2}	4200	67	35%	$3 \cdot 10^5$
$3 \cdot 10^7$	1,2	10^{-4}	3990	33	7%	$6{,}07 \cdot 10^3$
		10^{-3}	4840	14	40%	$1{,}43 \cdot 10^5$
		10^{-2}	4920	14	50%	$1{,}43 \cdot 10^6$

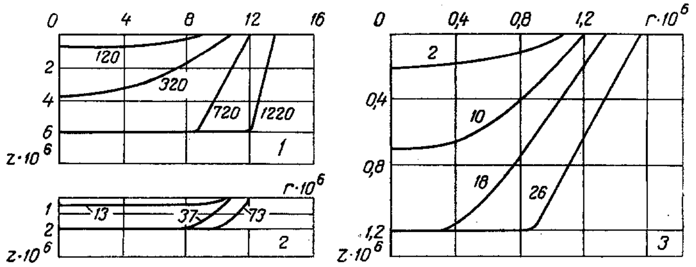

Fig. 2. Development of a melted zone in a copper film cathode; q cal/cm^2 · sec; r and z, m: 1) $q_B = 3 \cdot 10^6$, R_0 $R_0 = 10^{-3}$ cm, tp = (120–1220) · 10^{-9} sec; 2) $q_B = 3 \cdot 10^7$ $R_0 = 10^{-3}$ cm, tp = (13–73) · 10^{-9} sec; 3) $q_B = 3 \cdot 10^7$ $R_0 = 10^{-4}$ cm, tp = (2–26) · 10^{-9} sec].

If the source radius is 10^{-3} cm and the flux is 10^7 cal/cm^2 · sec or more, the evaporation rate is high even for v_{calc} larger than those actually observed by factors of 10–100; for instance, even within 100 nsec (a flux of 10^7 cal/cm^2 · sec), 50% of the total energy flux is consumed in evaporation. The observed velocities correspond to heating times larger by an order of magnitude, which means that such spot parameters cause a large part of the energy to be consumed in evaporation, while a smaller proportion is conducted inwards, and the result for fα under these conditions should be several times larger than that deduced without allowance for evaporation. If the source radius is 0.01 cm, the evaporation will be rapid for fluxes of $3 \cdot 10^6$ or more even with speeds much greater than $2.4 \cdot 10^3$ cm/sec. Then values of fα of 0.2 or more are quite realistic for a spot on a film cathode when there is vigorous evaporation.

The following are the effects of the heat source radius on the surface temperature and evaporation rate; if the heating times are such that the size of the heat source and the heating depth become comparable, the isothermal surfaces are very curved, and much of the heat supplied is removed in a radial direction. If R_0 is small, the heat loss sideways is large even when the surface temperature has not reached values substantially important for evaporation, so the temperature at the center of the source and energy flux in evaporation for given q_B are less the less the radius of the heat source.

These results show that certain operating conditions for the cathode spot mean that a given energy input to the depth of the metal may correspond to a variety of heat sources differing considerably in total deposited energy. Then a single track width may correspond to very different values of deposited energy and fα. If the flux in the spots is equal to or less than $3 \cdot 10^6$ cal/cm^2 · sec, and if $R_0 < 10^{-3}$ cm, one can get neglect evaporation and assume the f calculated without allowance for the latter. If the heat flux is greater than or equal to $6 \cdot 10^7$ cal/cm^2-sec, evaporation introduces a large contribution to the energy balance and fα for a given width track will vary with the radius of the heat source (heat flux). The final decision on α may be made from measurements of the mass of metal evaporated from the spot.

NOTATION

T	is the temperature;
a	is the thermal diffusivity;
λ	is the thermal conductivity;
γ	is the density of material;
g_{eva}	is the energy flux for evaporation;
η	is the coordinate of evaporation;
μ	is the evaporation rate;
D	is the flim thickness.

LITERATURE CITED

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