A Theory of the Production of Electrode Vapor Jets by Sparks and Arcs

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A thermal theory of the production of electrode vapor jets by arcs and sparks is presented which accounts satisfactorily for all known experimental results on vapor jets. The computed vapor jet velocities are in excellent agreement with those measured for mercury sparks by Haynes and for the high current carbon arc by the author and his co-workers. Theoretical predictions concerning the dependence of vapor jet production on the electrode materials provide a possibility for further checks of the theory.

THE ejection of electrode vapor, frequently in the form of vapor jets, is a phenomenon well known for many arc and spark discharges. Detailed studies of such vapor jets have been made by the author and his collaborators[1] (cf., also, Rohloff[2]) for the anode vapor jet of the high current carbon arc, and recently by J. R. Haynes[3] for certain mercury sparks. It is the purpose of this paper to show that the mercury vapor jets, discussed by Haynes, which are emitted from the positively and negatively charged mercury surfaces by his spark discharge, can be explained satisfactorily by a thermal theory developed earlier by the author for the explanation of jet phenomena in the high current carbon arc. The basic concepts of this theory are as follows:

Vapor jets are ejected from the electrodes of any discharge if sufficient energy for vapor production is transferred to the surface of either electrode by the incident electrons or positive ions accelerated by the anode or cathode fall, respectively. As a consequence of the continuous production of new vapor, the vapor produced in the time element just before is pushed away perpendicularly from the electrode surface by the vapor being formed, as if ejected from a nozzle in the electrode surface. The jet velocity then is uniquely determined by the vapor production per unit surface and the temperature-dependent vapor density.

We begin by computing the energy released per unit surface of an electrode. Now a liquid mercury electrode, because of its limited temperature, cannot emit an appreciable quantity of electrons or ions, so that the current immediately in front of it must consist exclusively of the charge carriers arriving at it, i.e., electrons at the anode, positive ions at the anode. We designate by j_a and j_c the current density at the anode and cathode, respectively, by ϕ the work function of the material for electron emission, and by V_a and V_c the respective anode and cathode fall by which the charge carriers are accelerated. An electron incident on the anode surface then releases here

$$W_a = j(V_a + \phi) \text{ watts/cm}^2. \quad (1)$$

At the cathode, also assumed not to emit electrons, a positive ion, incident with the kinetic energy eV_c, can spend the energy $e\phi$ in removing an electron from the metal and then returning neutralized into the vapor, thus releasing at the cathode the energy $e(V_c - \phi)$. It can, on the other hand, become bound to the metal and thus release its entire kinetic energy eV_c plus its binding energy. We shall not make a very large error in assuming that on the average the energy loss $e\phi$ of each neutralized ion will be compensated by the binding energy of other ions which become bound to the cathode, so that the energy released at the cathode will be

$$W_c = jV_c \text{ watts/cm}^2. \quad (2)$$

We designate furthermore by Q the energy necessary to evaporize one gram of electrode

[1] W. Finkelnburg, Zeits. f. Physik **114**, 714 (1939); **116**, 214 (1940); H. Schluge and W. Finkelnburg, *ibid.* **122**, 714 (1944); W. Finkelnburg and G. Heinzmann, *ibid.* 1948 (in press). Monograph: W. Finkelnburg, *Der Hochstromkohlebogen* (Verlag Julius Springer, Berlin, 1948); *The High Current Carbon Arc*, FIAT Final Report 1052, 1947 (PB-81644, Office of Technical Services, Department of Commerce, Washington, D. C.).

[2] E. Rohloff, Reichsberichte f. Physik **1**, 47 (1944).

[3] J. R. Haynes, Phys. Rev. **73**, 891 (1948).

material and heat it to the jet temperature (watt sec./g), and by δ the vapor density in grams per cm³. W/Q is then the quantity of vapor produced per second and per cm² at the electrode surface, and

$$u=(W/Q\delta) \text{ cm/sec.} \quad (3)$$

is the initial velocity of the electrode vapor jet ejected perpendicularly from the electrode surface as a result of the vaporization.

We now show that the values of the vapor jet velocity following from our theory are in agreement with the experiment for the mercury sparks of Haynes' as well as for our high current carbon arc, and that the theory furthermore accounts for the fact that, contrary to the mercury spark, a negative vapor jet is not observed in the high current carbon arc at currents below 400 amperes.

Data for the discharges under consideration and their electrode materials are presented in Table I.

The current density at the electrodes of the mercury spark was computed from dimensions taken from the published photographs and the current intensity; for the carbon arc it was known from our earlier work.[1] The same applies for the anode and cathode fall of the arc (the last one being not too accurate), while for the spark only the sum of both figures has been published to be 40 ± 5 volts, the distribution having been made by the author as plausible and in agreement with our general knowledge on mercury arcs. The vapor jet temperature near the electrodes has been measured by the author for the carbon arc, while it could be only estimated for the mercury arc; it is not too important, however, for the final result. The vapor density can be easily computed for the carbon arc (taking into account that according to spectroscopic evidence a large fraction of the vapor consists of diatomic molecules and some percent of the particles are rare earth atoms), while for the spark the accuracy of our knowledge of the vapor density is limited by the uncertainty of the extent to which the pressure in the vapor jet is equal to the gas pressure in the spark chamber (900 mm Hg). The vapor production energy, necessary for the production of one gram of vapor at jet temperature from the solid (or liquid) state, is well known from several independent measurements for the carbon arc and agrees satisfactorily with the theoretical estimates (vaporization energy 4.6×10^4 watt-sec./gram, heating energy 20 to $30RT$ per mole $=1.0$ to 1.7×10^5 watt-sec./gram).[1] For mercury the vaporization energy of only 300 watt-sec./gram is negligible, while the heating energy to 10,000°K, according to Rompe and Steenbeck,[4] is $40RT$/mole $=1.6\times10^4$ watt-sec./gram. For carbon arc electrode material, Q is thus about one order of magnitude larger than for mercury.

TABLE I. Data on the discharges and electrode materials.

			Mercury spark	Carbon arc
Anodic current density	j_a	amp./cm²	20,000	300
Cathodic current density	j_c	amp./cm²	100,000	5,000
Anode drop	V_a	volts	30	30
Cathode drop	V_c	volts	10	10
Work function	ϕ	electron volts	4.5	4.5
Vapor temperature	T	°K	10,000	7,000
Vapor density	δ	g/cm³	3×10^{-4}	5×10^{-5}
Specific vapor Production energy	Q	watt sec./g	1.6×10^4	1.3×10^5

The second essential difference between carbon and mercury electrodes (we consider the difference between arc and spark, in agreement with Haynes, as rather unimportant) follows from the energy balance at the electrodes. From Eq. (1) and the data of Table I we get for the energy released per second per unit anode surface:

$$W_a(\text{Hg spark})=7\times10^5 \text{ watt/cm}^2,$$
$$W_a(\text{carbon arc})=1\times10^4 \text{ watts/cm}^2.$$

The surface energy density at the anode thus is 70 times larger for the spark than for the high current carbon arc. At the cathode the difference is still more pronounced. As the mercury cathode cannot emit an appreciable quantity of electrons, the current at the cathode consists wholly of positive ions which here release, according to (2) and Table I, the energy

$$W_c=1\times10^6 \text{ watt-sec./cm}^2.$$

The carbon cathode, on the other hand, with its temperature of approximately 4000°K emits thermally an appreciable electron current, each electron carrying away from the cathode the energy $e\phi$. According to v. Engel and Steenbeck,[5] in this case the ion and electron currents in

[4] R. Rompe and M. Steenbeck, Ergeb. d. exakt. Naturwiss. 18, 335 (1939).

[5] A. v. Engel and M. Steenbeck, *Elektrische Gasentladungen* (Verlag Julius Springer, Berlin, 1934).

front of a thermally emitting cathode adjust themselves so that the energy released at the cathode by the arriving positive ions is equal to that required for the release of the electrons:

$$j_c^- \phi = j_c^+ (V_c - \phi), \tag{4}$$

if we designate by j_c^- and j_c^+ the electron and ion current densities at the cathode, respectively. In contrast to the mercury cathode, there is no energy available for vapor production at the carbon cathode. In agreement with the few reported experimental results, a vaporization of the carbon cathode can occur only if its current density is so large that the thermal electron emission can account for only a small fraction of the cathodic current, i.e., for

$$W_c = j_c^+ (V_c - \phi) - j_c^- \phi \gg 0. \tag{5}$$

This discussion has thus revealed why the high current carbon arc usually does not show a negative vapor jet, while Haynes with his mercury sparks finds two seemingly identical positive and negative vapor jets. The quantitative check of the initial vapor jet velocities u from formula (3) and the figures of Table I leads to the results which are listed and compared with the experimental values in Table II.

In the calculation neither the radiation of electrodes and vapors nor the heat conduction in the electrodes have been taken into account. The last contribution can be proved to be negligible, while the energy loss of the electrodes resulting from radiation is approximately compensated by an energy gain due to absorption of energy from the luminous vapor.[6] The accuracy of our results thus is limited mainly by that of the figures of Table I.

Considering these uncertainties, the agreement of our theoretical and experimental vapor jet velocities, according to Table II, is even better than we should expect. Our theory thus not only explains why the positive vapor jet velocities of mercury spark and high current carbon arc differ by two orders of magnitude and why a negative vapor jet usually is not ejected by the high current carbon arc, but accounts also, with a surprising accuracy, for the absolute values of vapor jet velocities. We take this agreement as evidence for the correctness of our basic theoretical ideas on the mechanism of vapor jet production.

[6] Cf. W. Finkelnburg, *Der Hochstromkohlebogen* (Verlag Julius Springer, 1948). p. 172 and 173.

TABLE II. Theoretical and experimental vapor jet velocities for mercury spark and high current carbon arc.

	Hg spark	Carbon arc
Computed velocity of positive jet (cm/sec.)	1.5×10^5	1.4×10^3
Observed velocity of positive jet (cm/sec.)	1.55×10^5	$1.5-4 \times 10^3$
Computed velocity of negative jet (cm/sec.)	2.1×10^5	0
Observed velocity of negative jet (cm/sec.)	1.9×10^5	0

Quite generally, we conclude from our theory that positive vapor jets ought to be observed in all discharges having a sufficient anodic current density. The initial jet velocity ought to be the larger, the higher the current density and anode drop, and the smaller the vapor production energy of the electrode material in question is. Negative vapor jets, on the other hand, according to our theory, should be ejected at the same current density only from cathodes of comparatively low temperature which cannot emit an appreciable amount of electrons, or at so high a current density that the thermal electron emission accounts for only a small fraction of the cathodic current. There is a relation, however, between current density and electrode material. High current density is not possible for a pure electron or ion current because of its high space charge; it requires a compensation of the space charge by charge carriers of the opposite sign. These can be formed, even in the last mean free paths in front of an electrode, by ionization of an evaporating metal, while there are not enough ionizable atoms (and of much higher ionization potential) near an electrode of sufficiently low vapor pressure. Any evaporation of an electrode thus, resulting from increased ionization, tends to increase the current density by contraction of the discharge and thus increases in turn the vapor production. Vapor jet production, requiring high current densities, therefore is much more probable when easily evaporated electrodes are used instead of metals like molybdenum or tungsten. Investigations with different electrode materials and current densities would permit a check of these predictions and thus of the correctness of our theory of vapor jet production which seems to describe satisfactorily the experimental results known at the present time.