ON THE CATHODE OF AN ARC DRAWN IN VACUUM

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Abstract

It has been found that the cathode is the only electrode which contributes vapor for the maintenance of an electric arc under very low gas pressure.

The velocity of this vapor was determined by two methods. Method 1 consisted of measuring the force of reaction of the vapor on the cathode and the rate of vaporization of the cathode material. Method 2 consisted of determining the force exerted by the vapor on a vane suspended in front of the cathode spot and the rate of vapor condensation on the vane.

Both these methods gave a vapor velocity of the order of $16\text{x}10^5$ cm/sec. A temperature of around 500,000° K results when this value for the cathode vapor velocity is substituted for c in the equation: $\frac{1}{2}mc^2=3\ KT/2$.

Introduction

A SERIES of experiments with electric arcs drawn in vacuum indicated that a jet of high-speed vapor is ejected from the cathode region of such an arc.[1] A description will be given in the following paper of an attempt to obtain quantitative data on the velocity of this cathode vapor.

For the sake of simplicity the word "vacuum arc" will be used as representing an electric arc under an air pressure of the order of a few microns. The exact pressure will be given in each particular case wherever this is of interest.

Description of Experiments

An electric arc can be drawn even in very high vacuum by separating two metal contacts carrying current of the order of a few amperes.

The arc is drawn initially in the vapor given off by the vaporization of the metal at the point of last contact[2] and may be maintained by the vapor which after contact separation continues to be given off from the contact surface.

A number of preliminary experiments suggested that a jet of metal vapor with considerable velocity was emitted from the cathode region. A knowledge of the velocity of this vapor jet is not only of value in connection with the determination of the temperature of the cathode region, but will also enable us to get a better quantitative picture of the conditions in the vacuum arc in general. Accordingly an investigation was undertaken based upon the following experiments:

1. Measurement of the force of reaction of the vapor on the cathode. Knowing the amount of metal vapor evaporated per unit time the velocity can be calculated.

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[1] R. Tanberg, Nature, Sept. 7, 371 (1929).

[2] J. Slepian, Journ. A.I.E.E., October, 1926, p. 930.

2. Determination of the momentum imparted by the vapor to a vane suspended in front of the cathode. Knowing the amount of vapor condensed on the vane per unit time the vapor speed can be obtained.

In Fig. 1 is shown the apparatus used for the tests outlined under #1 above. The copper cathode, *c*, consisted of a short copper cylinder, 0.6 cm diameter, on the end surface of which the cathode spot was located. A quartz tubing fitted tightly around the copper cylinder in order to limit the motion of the cathode spot. The cathode was fastened to a strip of aluminum which was suspended by two fine molybdenum wires from a suitable supporting frame mounted directly on the negative terminal leading through the wall of the arcing chamber. The pressure in the arcing chamber varied between 0.2×10^{-3} mm Hg at the beginning of the arcing to around 10×10^{-3} mm Hg at the finish. The arc current was supplied to the cathode through an iron wire which dipped into a pool of mercury, *P*, electrically connected with the negative terminal.

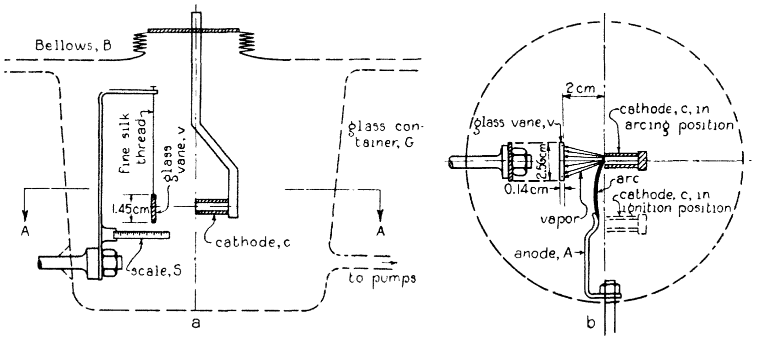

Fig. 1. Apparatus for determination of cathode vapor speed.

TABLE I. *Results of vapor speed determinations by cathode reaction tests.*

1 Test	2 Arc current (amps)	3 React. force (uncorr.) (gm)	4 Electrostatic force (gm)	5 Electrodynamic force (gm)	6 Total correction for electrodynamic and electrostatic forces	7
					grams	% of uncorr. react. force
353	11	198×10^{-3}	6.1×10^{-3}	4.8×10^{-3}	+ 1.3	0.66
352	16	265×10^{-3}	8.9×10^{-3}	10.3×10^{-3}	− 1.4	0.53
354	19	367×10^{-3}	10.6×10^{-3}	14.5×10^{-3}	− 3.9	1.06
355	19	367×10^{-3}	10.6×10^{-3}	14.5×10^{-3}	− 3.9	1.06
356	32	485×10^{-3}	18.0×10^{-3}	41.0×10^{-3}	−23.0	4.7

8 React. force (corr.) (gm)	9 gm/sec. evap. from cathode	10* $(C^2)^{1/2}$ cm/sec.	11 T° abs. temper. at cathode
199.3×10^{-3}	0.17×10^{-3}	6.3×10^{5}	6.8×10^{5}
263.6×10^{-3}	0.25×10^{-3}	14.6×10^{5}	5.45×10^{5}
363.1×10^{-3}	0.30×10^{-3}	16.8×10^{5}	7.25×10^{5}
363.1×10^{-3}	0.30×10^{-3}	16.8×10^{5}	7.25×10^{5}
$462.\times10^{-3}$	0.49×10^{-3}	13.1×10^{5}	4.37×10^{5}

* Based upon figures in column 8 and 9.

Thus the cathode was suspended so it would swing freely back and forth in a plane vertical to the cathode surface. The deflection was measured on a scale, S, located underneath the cathode. The instrument was calibrated for cathode deflecton against the corresponding force on the cathode surface.

The arc was formed by contact between the cathode and anode as indicated in Fig. 1b. As soon as the arc was playing the anode was moved to about 1.5 m away from the cathode. The deflection of the cathode during the arcing was of considerable magnitude and quite steady and could, therefore, be read with good accuracy on the scale provided for that purpose.

The results of a series of typical tests are compiled in Table I. Column 3 gives the force on the cathode as a function of the arc current given in column 2. Column 9 gives the amount of vapor in grams per second leaving the cathode during the arcing.

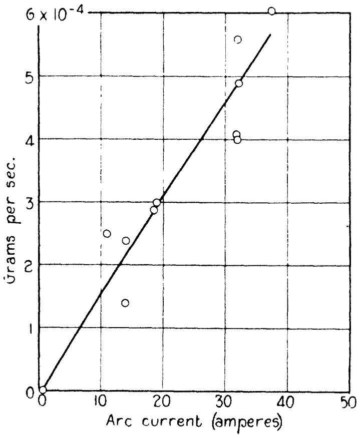

Fig. 2. Vaporization of copper cathode by arc in vacuum.

These last values are taken from the curve in Fig. 2 which is based upon a separate series of tests made under identically the same conditions as those existing during the measuring of the cathode reaction force. The cathode was weighed before and after each test and the time duration of the arcing was noted, thus determining the rate of vaporization of the cathode material.

Column 10 contains the root mean square velocities of the vapor leaving the cathode, calculated from the data given in columns 8 and 9 using the formula:-

$$(C^2)^{1/2} = 1.39K/m$$

where K = force in dynes on cathode.

m = mass in grams per second of metal evaporated from the cathode.

$(C^2)^{1/2}$ = root mean square velocity in cm/sec. of vapor leaving the cathode.

The development of this formula will be found in the appendix to this paper.

Considering the conditions under which the tests were made it is evident that the results should be corrected for possible radiometric, electrodynamic and electrostatic forces. A discussion of these corrections can also be found in the appendix.

The values of the cathode reaction force obtained when the above mentioned corrections are taken into account will be found in column 8 in Table I.

As will be seen later by the calculation of the corresponding temperature, the vapor velocities obtained are very high compared with what could be expected from conservative estimates of the temperature existing at the cathode. It was, therefore, thought desirable to check the results by the vane deflection method already referred to.

This was made with the apparatus shown in Fig. 3a and b. The cathode, *c*, was of the same design (copper cylinder surrounded by quartz tube) as used in the previous experiments. It was fastened to a metal rod which could be moved from outside the vacuum by means of the flexible bellows, *B*. The same pressure was maintained during these experiments as during the cathode reaction tests just described. The arc was formed by moving the cathode to touch the anode as indicated in Fig. 3b. As soon as the arc was playing, the cathode was moved back in front of the glass vane, *v*, consisting of a square piece of Pyrex glass. This was suspended by two fine silk threads from a supporting frame indicated in the figure. The deflection of the vane was read directly on the scale, *S*, and the force necessary to deflect the vane as a function of the deflection was determined.

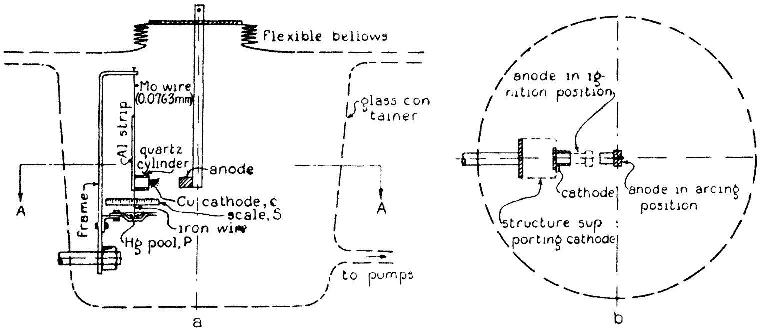

Fig. 3. Apparatus for measuring cathode vapor speed.

During a test the arc would play between the cathode and anode as indicated in Fig. 3b, while the vapor would be projected from the cathode spot directly against the vane deflecting this according to the momentum imparted to it by the impinging molecules.

The presence of this jet of high-speed vapor was not only evident from the definite deflection of the vane, but could also be realized visually by the sharply defined, faintly luminous, cone-shaped region, extending from the cathode spot to the vane. The results of these tests are given in Table II.

TABLE II. *Results of vapor speed determination by deflecting vane method.*

1 Test	2 Arc current (amps.)	3 Force on vane (gm)	4 Vapor condensed (gms/sec.) on vane	$(\overline{C^2})^{\frac{1}{2}}$ 5 cm/sec. R.M.S. vapor velocity
366	14.2	64×10^{-3}	42.6×10^{-6}	20.8×10^{5}
369	16.0	64×10^{-3}	53.7×10^{-6}	16.6×10^{5}
367	18.0	94×10^{-3}	$65\ \times10^{-6}$	20.1×10^{5}

The velocities in column 5 in this table were calculated by the same formula as previously used for calculating the vapor velocities from the cathode reaction tests, while *m* (column 4), representing the amount of metal vapor condensed on the vane per second, was obtained from the curve in Fig. 4, which is based upon direct measurements. It will be seen that the values for the cathode vapor speed obtained by this method agree quite well in the order of magnitude with the values obtained by the previous method.

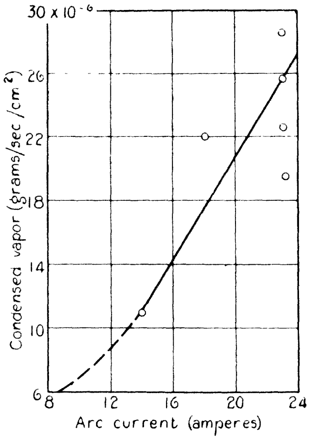

Fig. 4. Condensation of copper vapor on collector 2 cm from cathode.

When judging these results it must be remembered that it is practically impossible to prevent the cathode spot from traveling on the cathode surface. The amount of vapor hitting the vane may, therefore, vary somewhat with the location of the cathode spot.

The discussion in the appendix of possible corrections to these measurements will show that the effects from radiometric pressure, electrostatic fields etc., can be entirely neglected.

CALCULATION OF TEMPERATURE CORRESPONDING TO THE MEASURED VAPOR VELOCITIES

The knowledge of the speed with which the metal vapor is ejected from the cathode region enables us to calculate at least the order of magnitude of the temperature at the cathode by the well-known relations between the average kinetic energy and the absolute temperature of the molecules in a gas. It is believed to be justified to use in this connection the equation applying to three degrees of freedom of the molecule:

$$\tfrac{1}{2}m'\cdot C^2 = 3kT/2 \tag{1}$$

where m' is the molecular mass in grams; C^2 is the mean square of the velocity of the molecules in cm/sec.; K is Boltzmann's gas constant in erg/°Abs. and T is the absolute temperature.

The justification for using this form of the temperature-kinetic energy equation is the good agreement it gives with experimental results when applied to Stern's[3] and Eldridge's[4] measurements on velocities of molecules emitted from a hot metal surface under low gas pressure.

Substituting in Eq. (1) the values for the molecular velocities given in Table I give temperatures as shown in column 11.

General Discussion of Results

As will be realized, these temperatures are far in excess of even the most extreme temperatures ever measured in connection with any physical phenomenon of any duration. One must, however, remember that the space close to the cathode of an electric arc constitutes a very small volume with a large energy input where one, from only conservative estimates, could expect exceedingly high temperatures.

A similar case with large energy input into a small space constitutes the interesting experiments made by J. A. Anderson[5] with electrically exploded wires, during which he obtained estimated temperatures of 300,000°C.

Conclusion

The temperature existing at the cathode spot determined from the velocity of the cathode vapor is of the order of 500,000°K.

If this extreme temperature is confirmed by other investigators, our present ideas of what takes place at the cathode of a vacuum arc must be revised. The cathode region would then offer an excellent opportunity to study the very interesting physical conditions which must exist in a location with such an enormous temperature.

The writer wants to express his thanks to Dr. J. Slepian for the encouragement he has received from him during the preparation of this paper.

APPENDIX

Calculation of vapor velocities. A molecule will exert an impulse

$$\int K'dt = m'\cdot u \tag{2}$$

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[3] Stern, Zeits. f. Physik **2**, 49 (1920).

[4] Eldridge, Phys. Rev. **30**, 931 (1927).

[5] J. A. Anderson, Astrophys. J. p. 37. Jan. (1920).

on any surface which it is either leaving or striking. In this equation:

K' = force in dynes.
m' = mass in grams of the molecule.
u = component of velocity of molecule in cm/sec. perpendicular to surface.

The probability that a molecule in the vapor shall have a velocity component lying between u and $u+du$ is: $f(u).\ du$ assuming a certain velocity distribution. If n is the number of molecules per cm^3 of the vapor, the number of these which has a velocity laying between u and $u+du$ is: $n.f(u).\,du$.
The total number of molecules per cm^2 per second leaving the cathode region with velocities lying within this particular interval must therefore be:

$$\Delta\gamma = u(n\cdot f(u)\cdot du)\cdot\text{molecules/sec.} \tag{3}$$

where u = velocity perpendicular to the surface in cm/sec.

The force exerted by these molecules on the cathode per cm^2 is (from Eqs. (2) and (3)). $K'=(m'\cdot u)\cdot(u\cdot n\cdot f(u)\cdot du)$.

$$K' = m'\cdot n\cdot u^2\cdot f(u)\cdot du. \tag{4}$$

The total force per cm^2 of molecules leaving the cathode:

$$K = m'\cdot n\int_0^{\infty} u^2\cdot f(u)\cdot du. \tag{5}$$

By changing integration limits:

$$K = m'\cdot n\cdot\tfrac{1}{2}\int_{-\infty}^{+\infty} u^2\cdot f(u)\cdot du.$$

If u^2 denotes the mean square of the velocity component perpendicular to the surface:

$$K = \tfrac{1}{2}m'\cdot n\cdot u^2. \tag{6}$$

Since the vapor density $m'\cdot n$ is not practical to determine it is necessary to express this term by the amount of vapor leaving the cathode. The total number of moles per cm^2 leaving the cathode per second is found by integrating Eq. (3) from 0 to ∞: $\gamma = n\int_0^{\infty} u.f\,(u.)\ du.$if $|\bar{u}|$ denotes the average numerical value of the perpendicular component of velocity we have: $\gamma=\frac{1}{2}n\cdot|\bar{u}|$. Thus the total mass of the atoms leaving the cathode per second is: $A.m'.\gamma = A.m'.(\frac{1}{2}n.\,|\bar{u}|) = m$ or

$$A\cdot m'\cdot n = 2\frac{m}{|u|} \tag{7}$$

where m is total loss of cathode material during one second of arcing and A is the area of the cathode spot in cm^2. Making Eq. (6) apply to the whole

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[6] Richardson, "The Emission of Electricity from Hot Bodies" Edition 1921, pages 155 and 177.

cathode spot by multiplication with the cathode spot area "A" and combining it with Eq. (7) gives

$$K=(\overline{u^2}/|\bar{u}|m). \tag{8}$$

There is reason[6] to believe that the fundamental equations of Maxwell's velocity distribution theory can be used in connection with the conditions considered here. We can, therefore, substitute in equation (8) $\bar{u}^2=\frac{1}{3}\overline{C}^2$ and $|\bar{u}|=\frac{1}{2}\overline{C}$ which gives: $K=\frac{2}{3}C^{2,}/C\ (C^2)^{1,2}\ m\cdot$according to the Maxwellian velocity distribution function:

$$(C^2)^{1/2}/C = 1.08.$$

Hence:

$$(C^2)^{1/2}1.39K/m \tag{9}$$

which is the formula used for calculating the values given for the root mean square velocities in columns 10 and 5 in Tables I and II respectively.

The conditions at the vane are somewhat more complicated than assumed above because the existence of a Maxwellian velocity distribution in the gas at the vane surface may be questioned. However, the application of Eq. (9) to the data obtained from the vane deflection experiments will undoubtedly give values representing the correct order of magnitude of the R. M. S. velocity of the vapor striking the vane.

The values given in column 5 Table II which are calculated from Eq. (9) must therefore only be considered as serving the purpose of a rough check on the velocity values given in Table I.

DISCUSSION OF POSSIBLE CORRECTIONS TO VANE DEFLECTION TESTS

a. *Radiometric effect*—Due to the brilliancy of the cathode spot it was thought possible that the deflection of the vane during the experiments may have been affected by radiometric pressure. The tests recorded in Table III indicate, however, quite conclusively that the effect of radiometric pressure on the vane deflection must be of such small magnitude as to be negligible.

TABLE III. *Showing that variations in gas pressures do not affect the deflection of the vane.*

1	2	3	4		5	
Test	Arc current (amps.)	Distance cathode-anode (cm)	Pressure before test	(mm Hg) after test	Force on vane (gm)	Remarks
456	2.30	2.0	0.9×10^{-3}	56×10^{-3}	94×10^{-3}	vane deflect. did not vary with press. increase
457	"	"	63×10^{-3}	64×10^{-3}	130×10^{-3}	
458	"	"	0.2×10^{-3}	13×10^{-3}	130×10^{-3}	
459	"	"	0.2×10^{-3}	12×10^{-3}	94×10^{-3}	
460	"	"	0.2×10^{-3}	16×10^{-3}	130×10^{-3}	
461	"	"	0.2×10^{-3}	8.5×10^{-3}	130×10^{-3}	

During these experiments the gas pressure was measured by a McLeod gauge before and after each test allowing sufficient time for the pressure to equalize all through the vacuum system. The time required for equalization was very short since all tube connections were dimensioned so as to give a large ratio of diameter to tube length.

The pumps were shut off during each experiment. Since the leakage of the system was found to be negligible, the increase in pressure during each test represents gas given off from the electrode during the arcing.

Thus during test #456 which lasted several seconds the pressure increased from 0.9×10^{-3} mm Hg to 56×10^{-3} mm Hg but the deflection of the vane remained constant around the value given in column 5 in spite of the fact that the radiometric effect within the same pressure interval according to data by Westphal[7] should be expected to increase ten fold.

The difference in pressure at the end of tests 460 and 457 in Table III does not reveal any change in the force on the vane while the corresponding change in radiometric pressure according to Westphal's experiments should be about 28 percent.

A similar analysis of the other tests recorded in Table III points just as conclusively to the fact that the radiometric pressure on the vane can be entirely neglected during the writer's experiments.

b. Accumulation of charge on vane. If the vapor consisted of ions of one sign it would charge the vane up to a potential of the same sign as the charge on the vapor particles. The magnitude of this charge would increase until a sufficient field was set up to reflect the vapor particles back against the cathode. The momentum imparted to the vane by the vapor under such conditions would be about twice the momentum delivered to the vane if the particles condensed. It is, therefore, necessary to determine if such a reflection actually can have taken place during the tests recorded in the Tables I, II and III.

During a series of experiments the vapor from the cathode spot was made to condense on a metal plate which was kept under different potentials relative to the cathode. The metal plate was located in the same relative position to the cathode and anode as the vane during the previous experiments. The potential was varied between 0 and +60 volts without producing any effect upon the amount of condensed vapor.

Since the R. M. S. velocity of the vapor (15×10^{5}cm/sec.) corresponds to about 74 volts assuming singly-ionized Cu atoms, this potential interval should have been sufficient to show some changes in condensation had the vapor when reaching the vane been charged.

CORRECTIONS TO CATHODE REACTION TESTS

a. Radiometric effect: From the discussion in connection with the vane experiments it is probably safe to assume that the radiometric effect is negligible also at the cathode outside of the cathode spot proper. This assumption is justified on account of the extremely steep temperature gradient existing at the cathode spot which will limit the high temperature area to the spot itself.

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[7] Westphal, Zeits. f. Physik **1**, 92 (1920).

It remains, however, to be proved that the radiometric pressure at the cathode spot also will be of such small magnitude as to be negligible.

Knudsen[8] gives the following formula for the radiometric force as a function of temperature and gas pressure:

$$K = \frac{1}{2}p\cdot\left(\frac{T_1}{T_2} - 1\right) \tag{10}$$

where K is the radiometric force in grams/cm^2; p is the gas pressure in grams/cm^2, and T_1 and T_2 are absolute temperatures.

The good agreement obtained by Knudsen between experimental and calculated values within the pressure range existing during the writer's arcing experiments justifies the use of this formula in calculating the radiometric force at the cathode of the vacuum arc.

Assuming a temperature at the cathode of 700,000°K and a temperature of the surrounding parts of 300°K gives:

$$K = 328 \times 10^{-3} \text{ grams/cm}^2$$

from Eq. (10) for a pressure equal to 10×10^{-3} mm Hg. If we assume that the current density of 7200 amp/cm^2 found by Güntherschultze[9] for cathode spots on iron under atmospheric pressure also holds for a vacuum arc the cathode spot of a 20 amp. arc will have an area of 2.8×10^{-3} cm^2. Thus the total force on the cathode spot due to radiometric effects under the conditions specified will not exceed 0.92×10^{-3} grams/cm^2.

A comparison with the forces actually measured on the cathode spot shows that the radiometric effect also in this case can be entirely neglected.

b. Electrostatic force on the cathode. On account of the cathode drop an electrostatic force will be exerted on the cathode during the arcing in such a direction as to tend to move it into the arc. Since the cathode drop is known to be concentrated in a very small distance from the cathode surface the electrostatic force may be of such magnitude that it can not be neglected.

If S is the area in cm^2 over which the electric field extends at the cathode and E the field strength in absolute units per cm, the force in dynes exerted on the cathode is (assuming a dielectric constant $=1$) $F = S\cdot E^2/8\cdot\pi$.

Observations of the Stark effect[10] indicates a field strength at the cathode surface of the order of 10^5 volts/cm. Since the field at the edge of the cathode spot probably falls off very rapidly it should be correct to substitute for S in the above equation the area of the cathode spot determined from the current density observed by Güntherschultze.[9] The values thus obtained are given in column 4 Table I.

c. Electrodynamic forces. Due to the form of the current path in the apparatus shown in Fig. 1 an electrodynamic force can be expected to act upon the suspended cathode during the arcing, tending to increase its deflection. The correction for this will be found in column 5, Table I.

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[8] Knudsen, Ann. d. Physik **32,** 809 (1910).

[9] Güntherschultze, Zeits f. Physik **11,** 74 (1922).

[10] R. Seeliger, Physik der Gasentladungen, Leipsig, p. 282 (1927).