AN INTERPRETATION OF PRESSURE AND HIGH VELOCITY VAPOR JETS AT CATHODES OF VACUUM ARCS

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Abstract

Tanberg's conclusion, that the evaporating vapor from the cathode of a copper vacuum arc escapes with a temperature of about 500,000°K, which is based upon measurements of the repulsive force against the cathode, is shown to be unnecessary. The observed pressures can reasonably be explained in terms of the "accommodation coefficient" of the incoming Cu ions. It is thus shown that the observed pressures are accounted for if the positive ions retain about 2 percent of their incident kinetic energy after neutralization at the cathode.

IN A recent article in this journal[1] Mr. R. Tanberg has described some very pretty experiments on arcs drawn from a copper cathode *in vacuo*, which prove that there is a pressure of approximately 0.015 gm per ampere against the cathode, and a pressure of similar order of magnitude against an insulated vane placed about 2 cm in front of the cathode. These pressures, which were corrected for several minor disturbing influences, indicate the existence of material ejected with high speed from the cathode, and the experiments showed that this material is uncharged. Since copper evaporated from the cathode during the experiments, Tanberg identified the jet of high speed material with this stream of evaporated copper. The measurements of the amount of evaporation and the magnitude of the pressure led him thus to the conclusion that this vapor jet has a velocity of the order of 16 $(10)^5$ cm/sec and hence that "the temperature existing at the cathode spot determined from the velocity of the cathode vapor is of the order of 500,000 °K" . . . . "far in excess of even the most extreme temperatures ever measured in connection with any physical phenomena of any duration!" In view of the importance of this conclusion, if true, in the interpretation of arc cathode phenomena, it is important critically to examine Mr. Tanberg's work and the possibility of some less startling interpretation of his experimental results.

There is one part of Mr. Tanberg's calculations which shows entire failure to comprehend the nature of the electrostatic forces exerted on a cathode by the intense field at its surface. These are attrative forces, tending to pull the cathode toward the discharge, and Mr. Tanberg adds an estimated force of this type to the observed repulsion, to obtain the "corrected" repulsive force due to the reaction of the escaping vapor stream. He fails to note, however, that this strong field at the cathode arises from the positive ion space charge near it, that the attraction is mutually between cathode and

[1] Tanberg, Phys. Rev. **35**, 1080 (1929).

ions, and that when the ions strike the cathode, they deliver momentum to it at a rate which exactly counterbalances the electrostatic pull which they exerted on it before impact. That this follows from the elementary relation $\int Fdt = \int mdv$ is obvious and has long been recognized in such problems.[2] Thus this electrostatic correction should not have been made. It happens, however, to be only a few percent of the observed force, so that correction of this error does not essentially alter the evidence for a high speed stream of neutral particles escaping from the arc cathode.

There is, however, a phenomenon occuring at cathodes which appears quite adequate to explain Mr. Tanberg's results without invoking any unusual temperature of cathode spot. It is the occurrence of an "accommodation coefficient" of positive ions, as recently reported to the American Physical Society by Dr. Van Voorhis and the writer.[3] Positive ions, on striking the cathode, become neutralized but do not, on the average, give up enough of their kinetic energy to reach thermal equilibrium with the cathode. They rebound as neutral atoms from the cathode with some fraction β of their incident kinetic energy.

Athough, as we have seen, the impact of a charged ion against the cathode contributes nothing to the pressure against it (on account of the counterbalancing pull during its attraction to the cathode), nevertheless if the neutralized ion leaves the cathode with any momentum there is imparted to the cathode an equal opposite momentum. The following calculations show that this type of momentum transfer seems easily adequate to account for the pressures observed by Mr. Tanberg.

Let f be the fraction of the total current which is carried by positive ions at the cathode, and let β be the fraction of the incident energy of the ion which is retained after neutralization. β is approximately equal to $1-\alpha$, where α is the accommodation coefficient. The arc drop in a copper arc of high current density carried in copper vapor has been shown by Nottingham[4] to be 20.5 volts. It appears certain that the fall space in such an arc is so thin that ions make few if any collisions while traversing it.

Taking data from one of Mr. Tanberg's typical experiments (test No. 353) we calculate the following data:

Positive ion current at cathode	$11f$ amps
Mass of Cu ions striking cathode per sec	$0.00724f$ gm
Number of Cu ions striking per sec	$7.0(10)^{19}f$
Kinetic energy of an incident ion	$3.26(10)^{-11}$ erg
Total kinetic energy of ions striking per sec	$22.8(10)^{8}f$ erg
Total kinetic energy of neutralized ions leaving per sec	$22.8(10)^{8}f\beta$ erg
Total momentum of neutralized ions leaving per sec, which is equal to the pressure on the cathode	$5.86f(\beta)^{1/2}$ gm
If neutralized ions escape in random directions, as is likely, the resultant pressure is	$2.93f(\beta)^{1/2}$ gm

[2] Duffield, Burnham and Davis, Proc. Roy. Soc. **97,** 326 (1920).

[3] Van Voorhis and Compton, Phys. Rev. **35,** 1438 (1930).

[4] Nottingham, J. Frank. Inst. **207,** 301 (1929).

We now equate this to the observed pressure (corrected for "electrodynamical" disturbances but not for electrostatic disturbances as explained above) and obtain

$$2.93f(\beta)^{1/2} = 193.2(10)^{-3}.$$

We must now decide what value to use for the fraction f of current carried by positive ions at the cathode. Knowledge of this quantity is still woefully uncertain, even in the case which has been most studied, the mercury arc,[5] but all indications point to a value not far from $f=0.5$. Theoretically we would like perhaps to see a smaller value, but it seems impossible to find a much smaller value experimentally, unless we strain the interpretation of results. Furthermore, the present copper arc is probably of essentially the same type as the mercury arc.[6] So we shall provisionally assume that $f=0.5$. Solving, then, for β we find

$$\beta = 0.0174; \quad \alpha = 0.9826.$$

Thus the pressures observed by Mr. Tanberg would be accounted for if less than 2% of the incident energy of the ions were retained after neutralization. If we had assumed a smaller value of f, β would have come out larger and α smaller. The accommodation coefficient of Cu ions has never been measured, but from analogy with other ions of about the same atomic weight we might easily expect Cu ions to possess an accommodation coefficient as small as 0.9. Hence these considerations appear to give ample leeway for a reasonable explanation of Mr. Tanberg's results.

A possible objection to this theory based on the fact that Cu ions should condense on the cathode on striking it is met by the fact that their energies correspond to temperatures far in excess of the boiling temperature of the metal.

In conclusion it may be pointed out that this criticism does not alter Mr. Tanberg's basic conclusion regarding a high speed neutral vapor stream. It merely suggests an electrical mechanism for the acquiring of these speeds instead of assuming a terrifically high temperature at the cathode.

An interesting test of this interpretation is now being made by repeating Mr. Tanberg's experiments with a non-volatizing cathode of tungsten in a rare argon atmosphere. Here there is no possibility of an evaporated vapor stream like that considered by Mr. Tanberg, but the pressure effect due to the accommodation coefficient of argon ions is calculable directly from the work of Van Voorhis and Compton, combined with collector measurements to give directly the actual positive ion current.

[5] Compton and Van Voorhis, Proc. Nat. Acad. Sc. **13**, 336 (1927).

[6] Compton, Paper read before A.I.E.E., Detroit, June 1927.