THE COLD CATHODE ARC

By R. H. EATHER*

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Summary

Many theories have been proposed in the last 15 years to explain the observed high current densities associated with the cold cathode arcs. All of these theories are somewhat inadequate in themselves, but a combination of some of the more recent theories gives a satisfactory explanation of these high current densities.

I. INTRODUCTION

The term " cold cathode arcs " is used to refer to those arcs in which the cathode spot temperature does not exceed say 2000–3000 °C. They are the arcs of the low boiling-point metals such as iron, copper, mercury. The high current densities at the cathodes of such arcs cannot be explained in terms of simple thermionic emission. (These current densities are of the order of 10^5–10^6 A/cm^2.)

Several mechanisms have been suggested in the past 15 years to explain these high current densities. Some earlier theories were developed to account for current densities of 10^3 A/cm^2 and hence do not apply to the current densities now known to exist at cold cathodes. (For a review of earlier theories, see von Engel and Robson (1957) and Llewellyn Jones (1953).)

II. DISCUSSION

The modern theories, in brief, are as follows :

(i) Perhaps the most widely held view of the cold cathode arc mechanism is that the major part of the cathode current is carried by electrons extracted from the cathode by field emission, the high fields required being produced by the space charge of positive ions in the cathode fall space. Fields of the order of 10^6–10^7 V/cm account for the observed current densities. The threshold potential that keeps the electrons in the metal is lowered by this strong electric field, which permits them to escape from the metal in great numbers.

As the cathode fall is of the order of 10 V, it would have to extend over 10^{-5}–10^{-6} cm to produce the high fields for field emission. Smith's (1946) experiments on the thickness of the cathode dark space of the mercury arc (which is a cold cathode arc) show that field emission cannot account for the observed current densities in the mercury arc. Loeb (1939) also shows that field emission cannot account by many orders of magnitude for the high current densities observed in metal arcs.

* Physics Department, Newcastle University College, Tighes Hill, N.S.W. ; present address : Antarctic Division, Department of External Affairs, Melbourne.

(ii) A new theory suggested by Rothstein (1948) is applicable to arcs with low spot temperatures and relatively high spot mobilities, such as copper and iron. It is assumed that a region possibly 10^{-5} cm thick of very dense metallic vapour exists immediately adjacent to the cathode spot. This high density perturbs the atomic fields so that the normally sharp energy levels are spread into bands, including conduction bands. Metallic conduction is then possible from the cathode to this region, which is at a temperature high enough to emit thermionically into the plasma. The ions bombarding the cathode serve to maintain the high local density.

This theory is supported by Smith's (1946) observation that a continuous spectrum originates within 10^{-3} cm of the electrode surface.

Richardson's equation for thermionic emission is

$$j_c = AT_c^2 \exp(-\Phi/kT_c),$$

where j_c is the cathode current density and T_c the cathode hot-spot temperature. Φ is the work function of the metal, A a constant, and k the Boltzmann constant. T_c is given by Cobine (1941) as 2400 °K for the iron arc, so substitution gives $j_c \simeq 10^{-1}$ A/cm^2 which is obviously far too low.

Applying Rothstein's theory, T_c becomes T_v, the temperature of the dense iron vapour. Assuming that this dense vapour in the arc plasma is at the same temperature as the plasma itself and using Hefferlin's (1959) value of 4450 °K for T_v for the iron arc, substitution then gives $j_c \simeq 10^4$ A/cm^2. Again the theory does not explain the observed cathode current densities.

(iii) Another theory was suggested by von Engel and Robson (1957). They suggested that electrons are released from the cathode by the impact of excited atoms. The electrons gain energy in the cathode fall and produce excited atoms in the dense vapour. The radiation from the excited atoms diffuses out and by successive absorption and re-emission in the vapour is ultimately absorbed by atoms which strike the cathode. Positive ions are formed in the vapour by collisions between excited atoms and by electrons colliding with excited atoms. The space charge of the positive ions supplies energy for evaporation and transfers momentum to the evaporated atoms. The latter effect sets up a vapour density close to the cathode which is many orders of magnitude greater than elsewhere.

von Engel shows that the process of electron emission by excited atoms whose energy does not greatly exceed the work function is very efficient, and his theory accounts for the high current density of the mercury arc. The mercury arc is the best example of the proposed mechanism as all the excited states of the mercury atom have energies greater than the work function of the metal, and hence are capable of releasing electrons. For iron and copper cathodes, however, where a large proportion of the excited states have excitation energies lower than the work function, the efficiency of the process is greatly reduced.

Note, however, that von Engel has given a mechanism explaining a high vapour density near the cathode spot. This was previously assumed by Rothstein.

(iv) A new contribution was made by Cassie (1958). He suggested that in the pinch effect in a plasma, the inward radial force is balanced by an increase in gas pressure which is unbalanced axially. The plasma maintains its state of electrical neutrality under the pinch forces. If, however, the situation in the metal is considered, the fact that the positive charge centres, that is, the crystal lattice points, are not free to move means that the pinch effect forces are not balanced by an electron gas pressure but only by space charge forces. Thus the pinch effect sets up negative space charge in the region of high current density near the cathode spot. The effect of this negative space charge is to lower the effective work function Φ by $\Delta\Phi$.

Hence the Richardson equation becomes:

$$j_c = AT_c^2 \exp\left[-(\Phi - \Delta\Phi)/kT_c\right],$$

where $\Delta\Phi$ is given by

$$\Delta\Phi \simeq \mu\varepsilon J \Lambda^2 \exp\left[\frac{2}{m}(W + \Phi - \Delta\Phi)\right]^{\frac{1}{2}},$$

where μ and ε have their usual meanings, J is the current density, Λ is the slowing down length, and W is the Fermi energy. $\Delta\Phi$ has the value of 2–3 V for copper and $1 \cdot 5$–$2 \cdot 5$ V for iron (see Cassie 1958). Substituting for the case of iron and using Cobine's value of 2400 °K for T_c gives $j_c \simeq 1 \cdot 4 \times 10^2$ to $1 \cdot 7 \times 10^4$ A/cm^2. Again the theory does not explain the observed current densities.

However, if theories (ii), (iii), and (iv), each of which is somewhat inadequate in itself, are combined, then a reasonable explanation of cold cathode emission is obtained.

von Engel and Robson's theory gives a mechanism explaining a high vapour density near the cathode spot. Applying Rothstein's theory to this high density vapour accounts for current densities of the order of 10^4 A/cm^2 (for the iron arc). Now if the pinch effect which results in a lowering of the work function is also considered (as in Cassie's theory), the Richardson equation becomes

$$j_c = AT_v^2 \exp\left[-(\Phi - \Delta\Phi)/kT_v\right].$$

Substitution for iron now gives $j_c \simeq 5 \times 10^5$–5×10^6 A/cm^2, which is of the observed order. Similar calculations for copper give a j_c ranging from $2 \cdot 5 \times 10^6$ to $7 \cdot 5 \times 10^7$ A/cm^2, depending on the value of $\Delta\Phi$ chosen and on the value of T_v used (values of T_v quoted in the recent literature vary from 4500–6100 °C).

Thus the combined theories predict the observed current densities. The calculated current densities are very dependent on the value of $\Delta\Phi$ used, and more accurate values of $\Delta\Phi$ must be determined before any certainty can be placed on the validity of the calculated current densities.

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