High Temperature Plasma Properties from High Current Arc Stream Measurements

W. FINKELNBURG AND S. M. SEGAL
Engineer Research and Development Laboratories, Fort Belvoir, Virginia
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The high current arc stream in air, operated at currents between 150 and 250 amperes, with an axial temperature between 10,000 and 12,000°K, is shown to be a very uniform high temperature plasma. Probe measurements of the potential gradient along the axis of the arc stream, and of its effective diameter, lead to the conclusion that its plasma has a constant electrical resistivity of 1/100 ohm-centimeter, widely independent of the arc current. From this resistivity, the current density, the potential gradient and the plasma temperature, empirical values of the electron mobility, their relaxation length, and the effective ion cross sections in the plasma are derived. The value of the ion cross section agrees well with that computed from a theoretical formula of Druyvesteyn, but is by a factor smaller than those generally considered correct.

I. INTRODUCTION

THE high current arc stream in air, operated at currents between 150 and 250 amp., with an axial temperature between 10,000 and 12,000°K, deserves special interest as an example of an apparently very uniform high temperature plasma. It will be shown in this paper that simple potential-probe measurements make it possible to determine, partly directly and partly indirectly, a number of important plasma properties, and to draw conclusions which are believed to be of general theoretical interest.

Earlier investigations by one of us have shown that the contracted high current arc stream which forms automatically[1] in air containing traces of carbon vapor at currents above 100 amp., consists of a bluish-white narrow column which is surrounded by well-defined zones of different colors and decreasing temperatures. The diameter of the central column increases from the cathodic foot point to a constant value of approximately twice its original value, at about 6 to 10 mm from the cathode, depending on the arc length (Fig. 1). From the strong continuous spectrum, the absence of molecular spectra, and the broadening of the few emission lines present, we had concluded[1] that the central column is the arc stream proper which, with its high degree of ionization, conducts virtually the total arc current. Though this conclusion has, in general, been accepted as reasonable, no direct measurement of the effective electrical diameter of the arc stream existed. Nor was the potential distribution along the arc stream and its dependence on the arc stream parameters known with sufficient certainty, though Höcker, Schulz, and the author[2] had used an old preliminary gradient determination of the author's for calculating an axial temperature of the contracted arc stream of 11,700±700°K, in satisfactory agreement with the spectroscopic estimate. Accurate determinations of both missing properties of the arc stream are reported in this paper, and it is a gratifying result that the original arc gradient measurement of 10 volts/cm proves to be correct for the main part of the arc stream, so that the temperature[2] based on it remains valid.

II. MEASUREMENT OF POTENTIAL GRADIENT AND EFFECTIVE DIAMETER OF THE HIGH CURRENT ARC STREAM

For the measurement of the potential gradient and of the effective diameter for different distances from the cathode, a thin tungsten probe was whipped at a known constant speed through consecutive cross sections of the arc stream, each of which was one millimeter farther away (or closer to) the negative electrode than the preceding one. During each passage, the probe potential (with reference to one of the electrodes), the total arc voltage, and the arc current were recorded photographically by a Hathaway oscillograph. In passing through the arc stream plasma, the probe picks up a potential which, because of the high mobility of the electrons as compared to that of the positive ions, is always negative with respect to the actual plasma potential. However, because of the approximately constant temperature along the arc stream, this negative "contact potential" between probe and plasma is believed to be effectively constant for successive passages of the probe. The differences of the probe potential for successive passages consequently give the true arc stream gradient. The influence of the probe on the high current arc stream was studied by using a variety of probes and probe speeds. The amount of perturbation of the arc by the probe could be evaluated from the traces of arc voltage and arc current, which were recorded simultaneously with the probe voltage. As expected, the perturbation was the smaller the smaller the probe diameter. With a tungsten probe of 0.1-mm diameter which was covered by a thin glass tube (0.7-mm diameter) except for its point of 0.3-mm length, the perturbation of the arc remained within the accuracy of our recording device. Moreover, sequences of probe passages through the same cross section of the arc stream always gave the same probe potential, as did

[1] W. Finkelnburg, J. App. Phys. **20**, 468 (1949); *Hochstromkohlebogen* (Springer-Verlag, Heidelberg, 1948).
[2] K. H. Höcker and W. Finkelnburg, Zeits. f. Naturforsch. **1**, 305 (1946); K. H. Höcker and P. Schulz, Zeits. f. Naturforsch. **4a**, 266 (1949). The theoretical results of the latter paper agree closely with those derived in this paper, more directly we believe, from our measurements.

passages at different probe speeds. From these observations we conclude that neither temperature effects nor gas turbulence caused by the probes being whipped through the arc stream have any appreciable disturbing effect on our results. In general, probe speeds between 50 and 100 cm/sec. were used.

Figure 2 shows the potential distribution along the axis of the arc stream. The potential of a point approximately 1 mm from the cathode tip has been chosen as the reference zero, because the potential drop within the last millimeter which includes the cathode drop is not known accurately enough. Figure 3 shows the potential gradient (volts/cm) determined by differentiation of Fig. 2, along the arc stream axis; it decreases from 40 volts/cm near the cathode to a constant value of 10 volts/cm in the main part of the arc stream.

The effective electric arc stream diameter could be determined, at least approximately, from the arc voltage record under the reasonable premise that the arc voltage is disturbed only when the probe is in the arc stream proper where the essential electric conduction takes place. This effective electrical diameter of the arc stream proved to be much smaller than the apparent optical diameter, in agreement with our previously stated opinion that only the contracted whitish part with its continuous spectrum is the arc stream proper which carries the current, whereas the outer luminous zones are essentially heated by conduction from the arc stream proper.

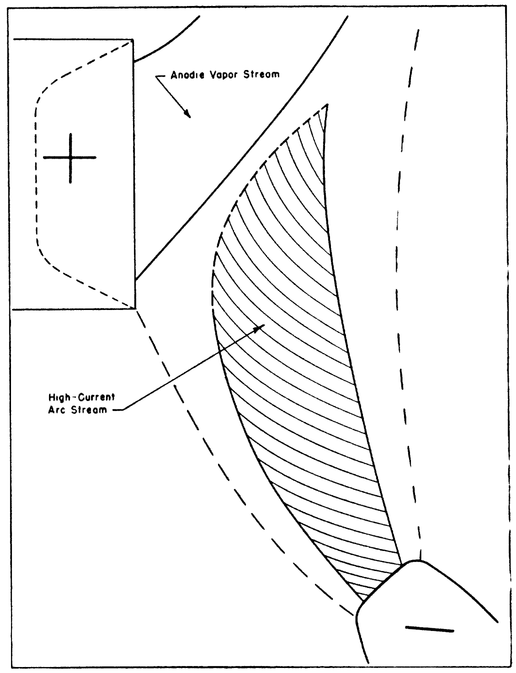

FIG. 1. Sketch of electrode arrangement and arc stream of the high current carbon arc.

III. EXPERIMENTAL RESULTS

(1) The arc stream gradient, plotted in Fig. 3 as a function of the distance from the cathode tip, is independent of the positive carbon material, of the total arc length, and particularly independent of the arc current, at least in the range from 150 to 250 amperes.

(2) The arc stream gradient decreases from an initial value of 40 to 50 volts/cm near the cathode towards a constant value of 10 volts/cm which is reached from 5 to 10 mm from the cathode, depending on the more or less slender shape of the arc stream. The gradient increases again near the anode, due to the effect of the vapors emanating from the positive crater (disturbed part of the arc stream).

(3) The effective electrical diameter of the high current arc stream agrees, within the limits of our accuracy, with that of the whitish contracted arc stream proper, mentioned above with its spectral characteristics indicating its high degree of ionization. This diameter increases, for a 200-ampere arc, from a value of 2 mm near the cathode to a value of a somewhat above 4 mm which is reached from 6 to 10 mm from the cathode.

(4) From (2) and (3) it follows that the arc stream gradient is, to a first approximation, inversely proportional to the effective cross section of the contracted arc stream.

(5) From (1), (4), and the known current densities in the different regions of the contracted arc stream (ranging between 5000 and 1000 amp./cm^2) there follows a surprising and important conclusion: The plasma of the contracted high current arc stream behaves, independently of the arc stream diameter, the arc current and the arc length, as a uniform plasma with an approximately constant resistivity of 1/100 ohm-centimeter or, conversely, with a constant electric conductivity of 1×10^{14} e.s.u. The electric conductivity of this high temperature plasma, consequently, is of the same order as that of graphite and only one order of magnitude below that of many metals.

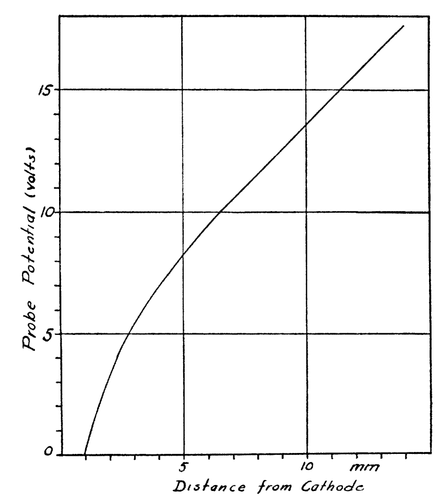

FIG. 2. Probe potential measured on the axis of the high current arc stream as a function of the distance from the cathode tip. The probe potential 1 mm from the cathode was chosen as the reference.

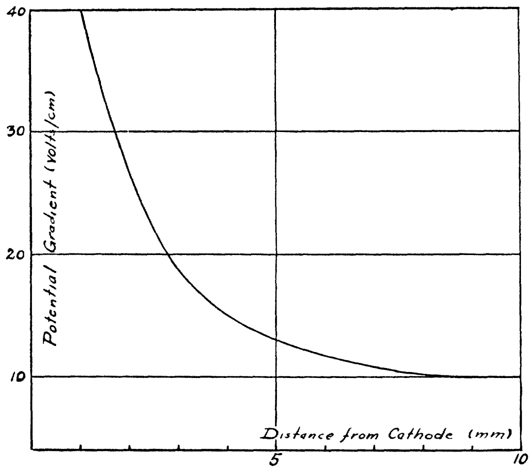

FIG. 3. Potential gradient (volts/cm) on the axis of the high current arc stream as a function of the distance from the cathode tip.

IV. DISCUSSION AND THEORETICAL CONCLUSIONS

From these experimental results a number of interesting conclusions can be drawn as to the behavior of this high temperature plasma if one last property is known; *viz.*, the degree of ionization. From the intensity of the continuous spectrum, which is a bremsspectrum of the discharge electrons,[3] it is apparent that the degree of ionization is by orders of magnitude higher than that of the low current arc stream. In agreement with this conclusion the Saha equation leads, according to a paper by Höcker and the author,[2] to a degree of ionization between 10 and 20 percent.

At atmospheric pressure and an average temperature of 10,000°K, we then have a gas density of 7×10^{17} atoms/cm^3 and an electron and ion density of approximately 1×10^{17} per cm^3. From this value of the electron density, and from the experimental current density in the arc stream, there is obtained an average electron drift velocity in the direction of the electric field decreasing from 3×10^5 cm/sec. near the cathode to 7.5×10^4 cm/sec. in the more distant parts of the arc stream, compared with a random thermal velocity of the electrons of 2×10^7 cm/sec. This result, incidentally, is evidence that there exists thermodynamic equilibrium in the arc stream, as the directed drift velocity is only one hundredth of the random thermal velocity. Taking into account the values of the arc stream gradient of Fig. 3 we compute an electron mobility b_e, identical for the whole contracted high current arc stream, as

$$b_e = 7.7\times10^3 \text{ cm}^2/\text{volt-sec.} = 3\times10^6 \text{ e.s.u.}$$

From the relation between mobility b_e and mean free path λ_e

$$b_e/\lambda_e = e/(3kTm)^{\frac{1}{2}},$$

we get an empirical value of the mean free path of the electrons in the plasma of

$$\lambda_e = 4\times10^{-4} \text{ cm}.$$

Now we equate the mean free path λ_e of the electrons with the theoretical relaxation length, i.e., the average path for which an electron loses half of its kinetic energy[4] by interaction with the plasma partners,

$$s = \gamma(kT)^2/e^4N.$$

N is the density of electrons and ions, calculated above, and γ is a numerical factor which, according to different theoretical approaches to the problem has values between 0.01 and 2. By equating the theoretical relaxation length, s, with our empirical value of the mean free path, λ_e, we find an empirical γ-value, valid for our high temperature plasma, equal to unity, in fair agreement with the theoretical computation by Druyvesteyn,[5] but in sharp disagreement with the presently prevailing opinion that γ should be of the order of 10^{-2}.

This check on the theory of the relaxation length which seems possible by means of our arc stream measurements, is of general theoretical interest, because this relaxation length and the effective cross section, Q_i, of the positive plasma ions computed from it are essential, but hitherto unknown, properties of any plasma.

It seems to be a safe premise that in our plasma, where every seventh atom is ionized, the positive ions with their extended Coulomb fields alone play the dominant role in terminating the mean free paths of the electrons. Computations confirm that the cross sections of the neutral atoms are far too small to account for the empirical mean free paths of the electrons. We thus are justified in writing

$$s = \lambda_e = 1/NQ_i.$$

where N is the ion density and Q_i is the effective cross section of the positive ions. Combining this with our result above that the factor γ is of the order of unity we have, for our high temperature plasma at least, the effective ion cross section

$$Q_i = e^4/(kT)^2.$$

Since the only existing experiments on relaxation lengths in a plasma have been made by Langmuir and Mott-Smith[6] in a low pressure mercury plasma of very low ion density (10^9 compared to our 10^{17} ions/cm^3) we believe that arc measurements like those reported here may contribute much to high temperature plasma research.

[3] W. Finkelnburg, *Kontinuierliche Spektren* (Verlag Julius Springer, Berlin, 1938).

[4] For this whole discussion compare the review of plasma physics by R. Rompe and M. Steenbeck, Ergeb. d. exakt. Naturwiss. **18**, 257 (1939).

[5] M. J. Druyvesteyn, Physica **5**, 561 (1938).

[6] I. Langmuir and H. Mott-Smith, Gen. Elec. Rev. **27**, 766 (1924).