FIELD DISTRIBUTION ALONG A LONGITUDINALLY STREAMLINED ARC IN A DC PLASMATRON

A. S. Vasil'kovskaya, L. I. Kolonina, A. D. Lebedev, and V. Ya. Smolyakov

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These measurements were made with potential probes and show that the voltage increases along the arc in the direction of gas flow. An explanation in terms of increase in temperature is proposed.

NOTATION

I is the arc current; G is the gas flow rate; E is the field strength; U is the potential; σ is the electrical conductivity; Q_c is the convective heat flux; α is the heat-transfer factor; T is the mass-average temperature; F is the surface of unit length; μ is the dynamic viscosity; T_a is the arc temperature; N is the Nusselt number; λ is the thermal conductivity; d is the electrode diameter; d_a is the arc diameter; R is the Reynolds number; ρ is the density deduced from T; W is the mean gas flow speed; S is the cross section of electrode, l is the distance along the axis from the inner electrode.

$$N = \alpha d_*/\lambda,\ d_* = d - d_a,\ R = \rho W d_*/\mu,\ F = \pi d_a.$$

1. These measurements were made in a dc plasma torch whose principles have previously been discussed [1] (Fig. 1). Electrode 1 is

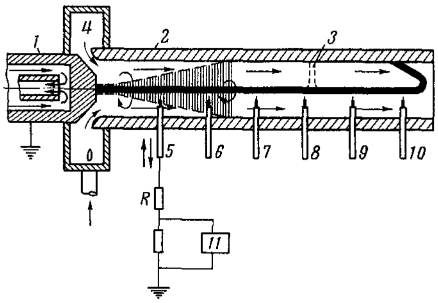

Fig. 1

made of copper and cooled by water, while electrode 2 is also of copper and is 250 mm long, with six holes 1.6 mm in diameter to admit adjustable probes. The gas is admitted via the eddy chamber 4. The probes are inserted and withdrawn by a fast solenoid. The position of the probe is indicated by a feeler working over a set of mutually insulated discs. The probe is a tungsten wire 0.17 mm in diameter enclosed in a quartz tube with 0.2-0.3 mm projecting. The probe moves at 100 cm/sec and is inserted in the arc for 10-20 msec. The probe signal is recorded by the oscilloscope 11, the resistance in the probe circuit being 360 kΩ. The current is recorded by an N-375 recorder.

The measurements were made with air at I = 40-160 A and G = = 5-15 g/sec with reversed polarity (long electrode as cathode, internal diameter 10 mm). The first probe was 50 mm from the anode; the others were at intervals of 40 mm. The number of measurements under given conditions ranged from 7 to 30.

2. Figure 2 shows typical measurements of the potential relative to the anode at I = 80 A and G = 11 g/sec; 1-4 are the probe signals, while 5 is a distance marker. The probe signals rise rapidly, and the width of the equipotential part increases away from the internal electrode (anode), because there is a thick layer of cold nonconducting gas near the internal electrode for any given R. However, the results do not give the diameter of the arc core as a function of position or the radial potential distribution.

The equipotential section shows that the plasma around the arc takes up a potential equal to that of the arc at that point within the error of measurement, provided that the point is far from the shunt area; signals from that area are difficult to interpret on account of the complicated shape of the equipotential surfaces produced by the arc loop. High-speed photography shows [1, 2] that the emitting diameter (certainly greater than the core diameter) varies little under analogous conditions and is only 3-4 mm.

The oscillograms of Fig. 3, a and b, reveal oscillations in the voltages at the probes near the internal electrode, which are due to variations in current and pressure associated with arc shunting in the long electrode. A probe in the shunt region (Fig. 3c) shows voltage variations characteristic of the arc voltage variations consequent on length change by shunting [3]. (The curves a-c of Fig. 3 are from the first, third, and fifth probes, respectively, and are on the same scale, the deflection for the third probe representing 320 V.)

3. Field measurements were made at I of 40, 60, 80, 100, and 120 A with G of 5, 11, and 15 g/sec; everywhere (except near the eddy chamber) there was a rise along the direction of gas motion. The mean E at l = 7 cm was 22-24 V/cm at G = 11 g/sec and 20-22 V/sec for 5 g/sec for I of 40-80 A, while at l = 14.5 cm the values were 32-35 and 27-28 V/cm, respectively. The present results for l = 7 cm agree with others [4] for identical arc conditions.

The probe signal, as recorded by a loop oscillograph, is not reliable in the shunted end (beyond the fourth probe for I of 40-80 A); the probe is outside the arc for part of the time, while the loop (working frequency 450 Hz) cannot follow the voltage variations during shunting (shunting frequency 2-9 kHz), and a cathode-ray oscilloscope is required, which may be calibrated by reference to the maximum potential, when the probe is certainly in the arc column. This gave E = 55 V/cm at I = 80 A and G = 11 g/sec at l = 21 cm.

Figure 4 shows U and E at points along the column for G = 11 g/sec and I = 80 A as derived from oscillograms similar to those of Fig. 4. The loop and cathode-ray recordings are virtually identical for the region free from shunting. The E curve beyond the first probe was deduced by differentiating the U curve; the dashed lines in the region between the first probe and the internal electrode are only assumed, since the distribution of U here may have features associated with the radial injection, where E may be much higher than in the region of longitudinal motion [5]. Moreover, the voltage drop near the electrode is not known precisely for these conditions.

4. There is a marked variation in E along the arc, which may be due mainly to change in heat-transfer conditions along the arc. We neglect radiative loss [6] and assume that the heat transfer from the arc is convective, which gives an approximate equation for the heat balance as

$$\sigma E^2 = Q_c. \tag{4.1}$$

But $Q_c = \alpha F \Delta T$; we represent the arc as a solid (which is reasonable, as the column has a sharp boundary) and consider the transfer

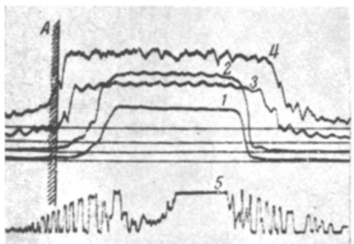

Fig. 2

by forced convection between coaxial cylinders, for which the relation of N to R may [7] be put as $N = CR^m$, with m = 0.8 for developed turbulence.

The α for the surface of the arc column is

$$\alpha = \frac{C\lambda}{d - d_a}\left[\frac{\rho W (d - d_a)}{\mu}\right]^m. \tag{4.2}$$

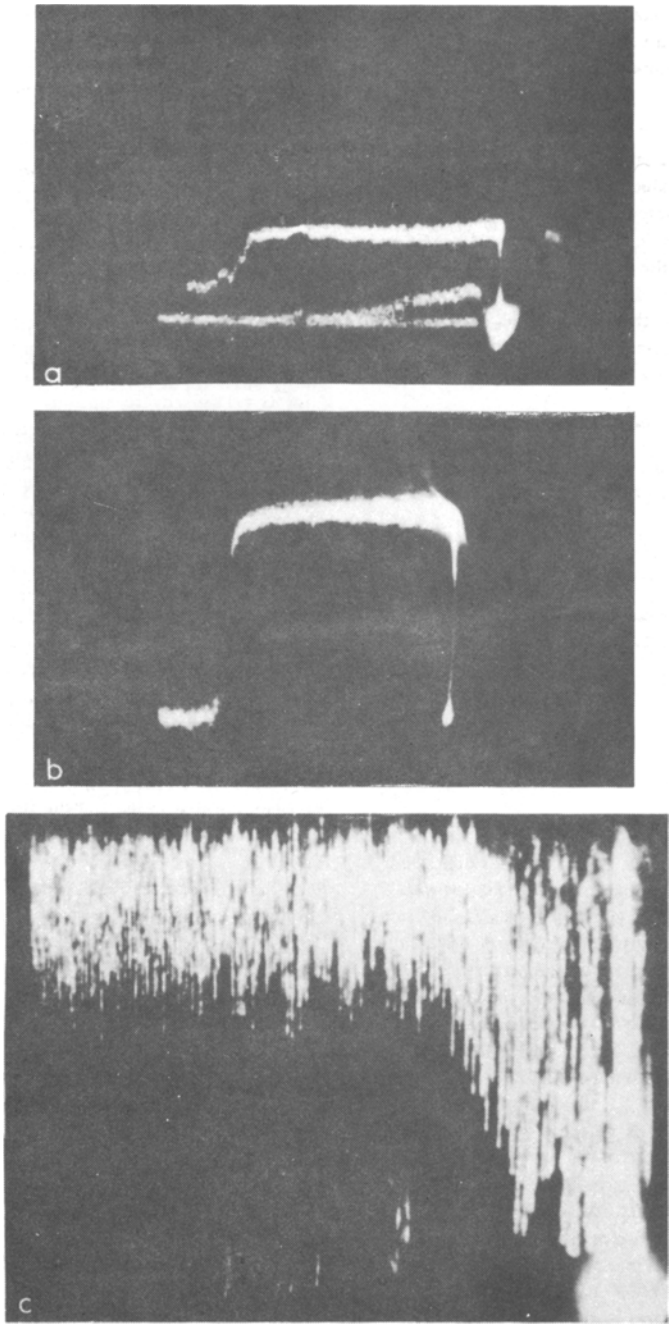

Fig. 3

Increase in T with l reduces ρ and increases W; $\rho W = G/S =$ = const for the steady state, while the molecular thermal conductivity λ is [8] given by the semiempirical formula

$$\lambda = \mu\,(aC + b) \approx a\mu C_p \quad (b \ll aC_p) \qquad (4.3)$$

in which a and b are constants; then

$$\alpha = \frac{C_1 C_p \mu^{1-m}}{(d - d_a)^{1-m}}. \qquad (4.4)$$

Then (4.1) and (4.4) give

$$E = \left(C_2\, \frac{C_p \mu^{1-m} (T_a - T)\, d_a}{\sigma\, (d - d_a)^{1-m}}\right)^{1/2}. \qquad (4.5)$$

To estimate T_a, and hence σ, we assume that d_a is constant; then E is dependent on T directly and via μ and C_p. E varies

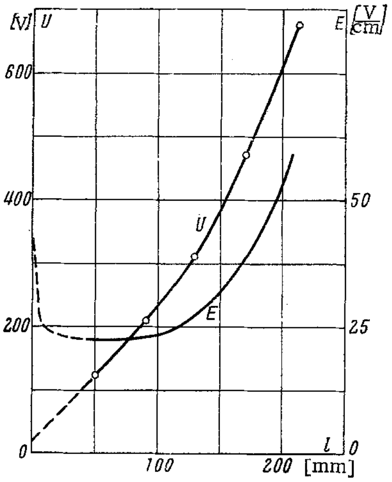

Fig. 4

roughly as $\mu^{1/2(1-m)} C_p^{1/2}$ for low T and $T_a \gg T$. Also, μ is roughly proportional to $T^{1/2}$, while C_p varies with T in a manner dependent on the gas. For monatomic gases, C_p increases monotonically with T up to the onset of ionization, while more complex gases in addition show effects from molecular dissociation, which occurs at relatively low T. For example, the peak in C_p for oxygen due to dissociation occurs at 3500°K near atmospheric pressure, and C_p increases by over a factor three between 2000 and 3500°K. This rapid rise in C_p should, from (4.5), produce a sharp rise in E in this temperature range, while the change in E should be slight (about 10%) between 300°K (inlet temperature) and 2000°K.

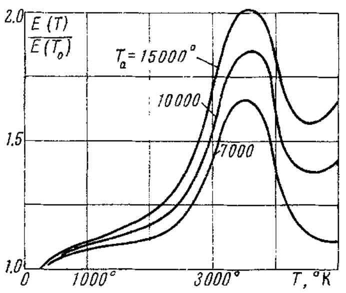

Fig. 5

Figure 5 shows curves for $E(T)/E(T_0)$ as a function of T calculated from (4.5) for three arc column temperatures (T_0 = 300°K). It is found [8, 9] that the arc column temperature under conditions close to those used here is 7000 to 15 000°K. The observed trend in E is thus in general agreement with the prediction. Figure 5 also shows that there is a local minimum in E between the temperatures corresponding to the dissociation of oxygen and nitrogen (roughly at 4500°K). This was not observed in the present experiments because the maximum temperature in the accessible region was only 3000–3500°K.

The shunting oscillations may also affect the distribution of E, so it is of interest to determine the distribution of E under the present conditions, except that shunting is absent (for a fixed length).

5. Consider the effects on E from change in G subject to the assumptions of section 4; from (4.5), with d and d_a constant but G variable, we have

$$E = C_3 G^{1/2m} \mu^{1/2(1-m)} C p^{1/2} (T_a - T)^{1/2}. \qquad (5.1)$$

E obviously increases with G; but increase in G by a factor n should not increase E at a given point in the region with T < 3500°K by a factor $n^{m/2}$, since increase in G reduces T at that point, which reduces the product $\mu^{1/2(1-m)} C_p^{1/2} (T_a - T)^{1/2}$ for $T_a \gg T$, especially in the region of rapid variation in C_p. On the other hand, the rise in C_p should accentuate the variation of E with G for points where increase in G reduces T from 4500 to 3500°K. The E–G dependence calculated from (5.1) agrees roughly with experiment.

Figure 6 shows observed curves 1–5 for E as a function of I for points at l of 5, 6, 7, 8, and 9 cm with G = 5 g/sec. The curves for G = 11 g/sec are similar. The minimum occurs at 50–80 A. Similar results have been reported for stabilized arcs condensed by rings [9], burning in narrow slots [8], in narrow cylindrical channels [8], and in the present apparatus fitted with a quartz tube.

A curve with a minimum has also been reported [10] for an arc stabilized by a tube wall. A curve of this shape arises because σ and λ vary with T_a, which itself is dependent on I. The E–I curves are of the same general form for different methods of stabilization, so the cause of the minimum in E = f(I) would appear to be the same.

The evidence, both theoretical and experimental, on arcs of the present type is very inadequate, in spite of its importance to the arcs used in plasma torches, especially in relation to calculation of arc length for sources with self-stabilizing arc length [1, 10].

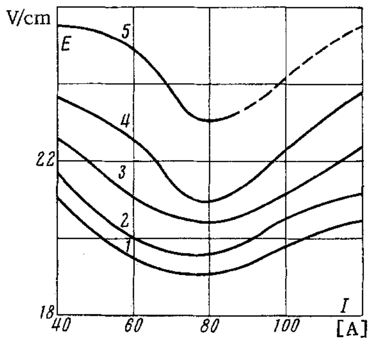

Fig. 6

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Editorial note*: This article is an attempt to calculate theoretically the electric field strength E and to explain why it increases along the channel. However, the authors made the following errors.

1. In the energy conservation equation (4.1) the power σE^2 per unit volume of arc is taken to be equal to the heat loss Q_c through the surface of a unit of arc length. The dimensions of these quantities are different: the formulas based on (4.1) are therefore erroneous. Equation (4.1) should be replaced by

$$\frac{\pi d_a^2}{4}\sigma E^2 = Q_c$$

where σ is the electrical conductivity of the plasma and d_a is the diameter of the arc column.

2. The authors assume that the plasma temperature T_a within the arc and the diameter d_a of the arc column are constant, and then they attempt to investigate the change in E along the channel. This procedure is incorrect, since constant T_a (and hence σ, as the authors assume) and d_a (constant arc current along the channel) would mean constant E, as Ohm's law directly implies:

$$I = \frac{\pi d_a^2}{4}\sigma E$$

In view of this the calculations for E as well as the figures and conclusions of the article are erroneous.

An example of the fact that the results are invalid can be seen in Fig. 5. This figure indicates that, for given d_a and the above, the higher T_a the greater the value of E. In fact, as Ohm's law shows, the reverse is true.

V. E. Ionin

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