VOLTAGE–CURRENT CHARACTERISTICS OF AN ARC IN AN ANNULUS MOVING UNDER A MAGNETIC FIELD

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Voltage–current relationships are presented in dimensionless terms for the high-current arc rotating in an annular gap under the influence of a magnetic field; air passes through the gap. It is found that one can neglect the effects of the air flow if the speed of the air is small.

There are several papers [1-3, 5] on the voltage–current characteristics of high-current arcs moving in response to magnetic fields; the basic quantity employed is an energy one, which takes into account the heat lost from the arc due to the gas flow. The differences between the approaches lie only in the way of choosing the arc blowing speed; in [1, 3, 5] the velocity used is that of the arc in response to the magnetic field, while in [4] the speed is that of the external gas flow perpendicular to the direction of rotation of the arc.

The arc speed is usually greater than the axial speed of the gas, and it is the main factor determining the heat transfer, so it would be preferable to use it as the definitive quantity if it were a known one; but this speed itself is dependent on the burning conditions, and any dimensionless quantity containing it cannot serve as an argument in an equation in terms of dimensionless quantities, so a survey in terms of the arc rotation speed merely represents a correlation between functions.

In [7, 8] there is a criterion for such an arc in which the rotational speed is expressed via other known parameters; if there is no gas flow, this takes the form

$$\Pi_1 = \rho_0 h_0^2 \sigma_0^2 \delta^5 B / I^3.$$

The experimental results of [2] have been surveyed [6, 8] to show that this single quantity alone is often sufficient to describe the voltage–current characteristics of high-current arcs moving in response to electromagnetic fields between parallel electrodes in the absence of gas flow. This is particularly so for a rotating arc, because the gas surrounding the arc is heated and the difference between the gas densities in the arc and in the surrounding space is less. The arc voltage has a certain spread, due mainly to the randomness in the arc motion, so the effects of the small additional air speed may lie within this spread. In that case, the air flow may be neglected entirely, and one can use formulas obtained for zero flow speed. This raises the question of the importance of the external flow, and how small the speed must be before its effect can be neglected. Also, it is desirable to elucidate the effects of curvature in the annular gap on the voltage–current characteristics.

We have examined the voltage–current characteristics of high-current arcs rotating in response to a magnetic field in an annular gap with an air flow (Fig. 1); the current varied from 125 to 900 A, while the induction of the magnetic field varied from 0.085 to 0.290 Tl, and the gas flow rate (air) varied from 0 to 14 g/sec, while the distance between the electrodes was 3 or 6 mm with a constant diameter D = 40 mm for the outer electrode. The arc voltage varied from 50 to 255 V, while the gas speed in the gap was 0-33 m/sec, and the arc speed was 66-450 m/sec. The maximum distance traveled by the cold gas during one turn of the arc was 58.5 mm. The arc then moves in cold gas, whereas at zero flow rate it moves in a hot medium; consequently, the experiments covered a wide range of arc conditions.

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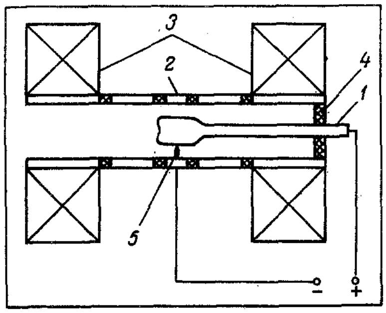

Fig. 1

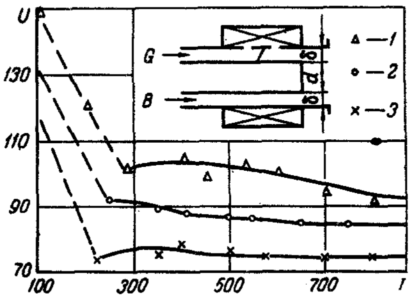

Fig. 2

Fig. 1. Scheme of experimental installation: 1, 2) electrodes; 3) solenoids; 4) insulator; 5) arc.

Fig. 2. Voltage–current characteristics of arc (D = 40 mm, δ = 6 mm, G = 5.5 g/sec): 1) B = 0.29; 2) 0.12; 3) 0.085 Tl.

This apparatus differed from one for heating gas in that the width of the ring was small (not more than 7 mm), which restricted the oscillation of the arc along the direction of the outer electrode [9].

Figure 2 gives voltage–current characteristics; initially, the voltage falls sharply as the current increases, but thereafter there is little change.

The figure also shows that the arc voltage is dependent on the magnetic field; the voltage at first increases rapidly with the field, but then the increase becomes slower, which may be due to gradual stabilization of the speed and arc size. On the other hand, measurement of the rotational velocity (not reported here) showed that the speed at first decreased rapidly as the gas flow rate increased, thereafter tending to a certain constant limit. The gas flow rate therefore influences the arc not only directly but also via the rotation rate.

The air flow produces cooling additional to that due to the rotation of the arc column, and Π_1 is the basic criterion for the flow-free condition. If the change in the generalized function $\Pi_2 = U\delta\sigma_0/I$ in response to the flow of cold gas is important, the standard deviation S on introducing the additional number for the air flow should be reduced; but if the change is only minor, then S should increase, since then the sum of the squares of the deviations is practically unaltered, while the number of independent parameters increases by 1.

To obtain increased accuracy, the results were surveyed separately for the parts of decreasing arc speed and constant arc speed, on the assumption that the gas speed influences mainly the convected heat transfer between the arc column and the surrounding medium. The following criterion takes into account the convective heat transfer when there is a flow of cold gas:

$$\Pi_3 = \rho_0 h_0 \sigma_0 \delta^3 W / I^2 .^*$$

The experimental values show that we can take $\Pi_3 = 3 \cdot 10^{-3}$ as the boundary between the regions of appreciable and slight influence from the gas speed; Fig. 3 shows the results. For $\Pi_3 < 3 \cdot 10^{-3}$, the experimental values are represented by the following formula with a standard deviation of 12.6%:

$$\frac{U\delta\sigma_0}{I} = 0.677 \left(\frac{\rho_0 h_0^2 \sigma_0^2 \delta^5 B}{I^3} \right)^{0.367} \left(\frac{\delta}{D} \right)^{0.533} \exp\left(-3.79 \rho_0 h_0 \sigma_0 \delta^3 W / I^2\right); \qquad (1)$$

and for $\Pi_3 > 3 \cdot 10^{-3}$ the corresponding formula is

$$\frac{U\delta\sigma_0}{I} = 2.14 \left(\frac{\rho_0 h_0^2 \sigma_0^2 \delta^5 B}{I^3} \right)^{0.303} \left(\frac{\delta}{D} \right)^{-0.169} \left(\frac{\rho_0 h_0 \sigma_0 \delta^3 W}{I^2} \right)^{0.084} . \qquad (2)$$

The coefficient of variation in this case is 9.6%. These formulas show that the arc voltage falls slightly as the gas flow increases at first, but rises again slightly after passing through a minimum.

However, the numerical values of the coefficient to Π_3 in (1) and the corresponding power in (2) show that the axial flow speed has only a minor effect, and this can be neglected for rough purposes, so a single formula can then be used for the approximation, which does not contain the gas flow rate. Figure 4 shows

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* The values of σ_0 and h_0 were taken from [10], while ρ_0 was calculated from h_0 at atmospheric pressure.

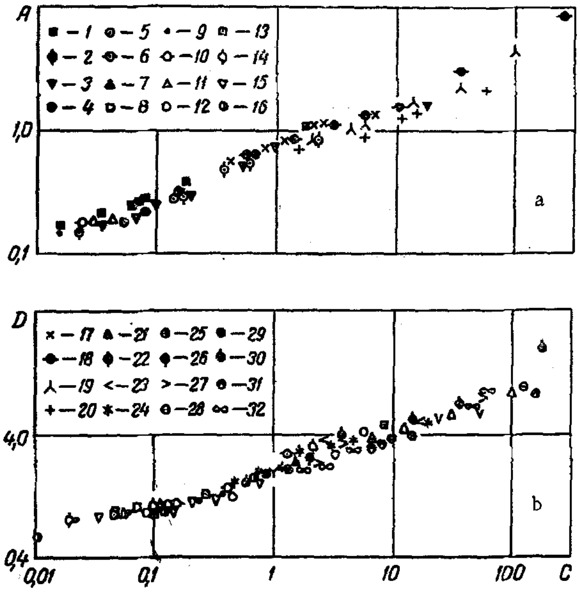

Fig. 3

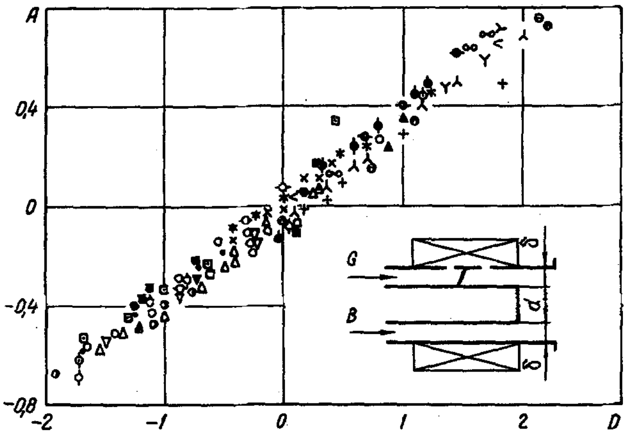

Fig. 4

Fig. 3. Generalized voltage–current characteristics for small and large air speeds: a) $\frac{\rho_0 h_0 \sigma_0 \delta^3 W}{I^2} < 3\cdot 10^{-3}$; b) $\frac{\rho_0 h_0 \sigma_0 \delta^3 W}{I^2} > 3\cdot 10^{-3}$, $A = \frac{U\delta\sigma_0}{I} \Big/ \left(\frac{\delta}{D}\right)^{-0.535} e^{-37.9\rho_0 h_0 \sigma_0 \delta^3 W/I^2}$, $D = \frac{U\delta\sigma_0}{I} \Big/ \left(\frac{\delta}{D}\right)^{-0.169} \frac{\rho_0 h_0 \sigma_0 \delta^3 W}{I^2}$, $C = \frac{\rho_0 h_0^2 \sigma_0^2 \delta^5 B}{I^3}$, δ = 3 mm; G = 0: 1) B = 0.085 Tl; 2) 0.12; 3) 0.23; 4) 0.29; G = 5.5 g/sec: 5) B = 0.29 Tl; 6) 0.12; 7) 0.23; 8) 0.085; G = 9.2 g/sec: 9) B = 0.085 Tl; 10) 0.12; 11) 0.23; 12) 0.29; G = 14 g/sec: 13) B = 0.085 Tl; 14) 0.12; 15) 0.023; 16) 0.29; δ = 6 mm; G = 0: 17) B = 0.085 Tl; 18) 0.12; 19) 0.23; 20) 0.29; G = 5.5 g/sec: 21) B = 0.29 Tl; 22) 0.12; 23) 0.23; 24) 0.085; G = 9.2 g/sec: 25) B = 0.085 Tl; 26) 0.12; 27) 0.29; 28) 0.29; G = 14 g/sec: 29) B = 0.085 Tl; 30) 0.12; 31) 0.23; 32) 0.29.

Fig. 4. Generalization of voltage–current characteristics for the velocity range. Notation is the same as in Fig. 3: $A = \lg\left(\frac{U\delta\sigma_0}{I}\right) + 0.374\lg\left(\frac{\delta}{D}\right)$, $D = \lg\left(\frac{\rho_0 h_0^2 \sigma_0^2 \delta^5 B}{I^3}\right)$.

the evidence presented in this way without allowance for the flow rate in the form

$$\frac{U\delta\sigma_0}{I} = 0.965\left(\frac{\rho_0 h_0^2 \sigma_0^2 \delta^5 B}{I^3}\right)^{0.37}\left(\frac{\delta}{D}\right)^{-0.379} \tag{3}$$

The coefficient of variation for the latter formula is 11.4%, which is less than for (1) but somewhat larger than for (2). This shows that the convective heat transfer is largely unaffected by the axial gas flow when the speed of this is close to zero; there is some effect at higher gas speeds but this is still quite small.

It is of interest to compare (3) with the speed of the arc over parallel electrodes in the absence of gas flow; for instance, the data of [2] can be represented via Π_1 in the form

$$\frac{U\delta\sigma_0}{I} = 1.385\left(\frac{\rho_0 h_0^2 \sigma_0^2 \delta^5 B}{I^3}\right)^{0.326}. \tag{4}$$

The coefficient of variation here is 14.6%; the power for Π_1 and the standard error in (3) are similar to those for (4), so low gas speeds allow one to obtain simple general formulas, which incorporate only convective heat transfer due to the motion of the arc in response to the magnetic field.

Of course, we have to consider what velocity is small enough for the effects to be neglected; for this purpose we compare the axial gas speed with the tangential velocity of the arc, which was also measured in these experiments.

The axial speed in these tests was 33 m/sec at the highest, which was 46.4% of the arc speed measured in the same run; this speed is certainly not small, and these are the conditions found in most arc heaters using concentric electrodes. Consequently, the simplified formulas that do not contain the flow rate may be used at least when the ratio of the arc speed to the cold gas speed in the gap is greater than 2.

There is a marked difference between the powers used with $\Pi_4 = \delta/D$ in formulas (1) and (2); (2) relates to higher cold gas speeds in the gap, so this means that there is a relation between the curvature and the flow speed: the effects of electrode curvature become less as the gas flow rate increases. The curvature affects the periodic arc shunting, and consequently the mean arc length; as the gas flow rate increases, the arc is drawn out in the azimuthal direction (because ions are carried along), and also along the electrodes. In that case the arc length is determined more by the gas flow rate than by the curvature.

It is also desirable to examine the effects of some numbers other than Π_3 and Π_4; results for our arcs enable one to determine which of these are the most important. The arc characteristics for the case of parallel electrodes indicate that there is a certain influence from the magnetic-pressure number $\Pi_5 = B^2/\mu_0 P$; when this is introduced, we get instead of (4) that

$$\frac{U\delta\sigma_0}{I} = 0.866\left(\frac{\rho_0 h_0^2\sigma_0^2\delta^5 B}{I^3}\right)^{0.388}\left(\frac{B^2}{\mu_0 P}\right)^{-0.085}. \tag{5}$$

The coefficient of variation is here reduced to 7% (by more than a factor 2).

However, the effect from introducing Π_5 is less for a blown arc in an annular gap; even if the approximations are performed separately, we get the following formulas instead of (1) and (2):

$$\frac{U\delta\sigma_0}{I} = \left(\frac{\rho_0 h_0^2\sigma_0^2\delta^5 B}{I^3}\right)^{0.37}\left(\frac{B^2}{\mu_0 P}\right)^{-0.094}\left(\frac{\delta}{D}\right)^{-0.598}\exp(-8.88\rho_0 h_0\sigma_0\delta^3 W/I^2), \tag{6}$$

$$\frac{U\delta\sigma_0}{I} = \left(\frac{\rho_0 h_0^2\sigma_0^2\delta^5 B}{I^3}\right)^{0.337}\left(\frac{B^2}{\mu_0 P}\right)^{0.04}\left(\frac{\delta}{D}\right)^{-0.24}\left(\frac{\rho_0 h_0\sigma_0\delta^3 W}{I^2}\right)^{0.035}, \tag{7}$$

which have a coefficient of variation of 9.1%.

Higher accuracy (3.5%) is attained for small Π_3, whereas for $\Pi_3 > 3\cdot 10^{-3}$ the gain in accuracy is only 0.5%, which indicates that the effects of Π_5 become less as the gas flow speed increases, which is confirmed also by the reduced power to Π_5, which so far is difficult to explain. Perhaps there is a change in the effects of the arc's magnetic field as the oscillations of the arc along the axis increase.

Note also the power to Π_3; in (2) and (7) it is positive, which indicates increase in heat loss and corresponding increase in arc power as the gas flow rate increases, which agrees well with physical concepts of the mechanism. However, there is a minor sign to W in (1) and (6), which clearly conflicts with this mechanism, and that is to be understood, since the fall in the voltage occurs not via the direct influence from W on the convective heat transfer but via a reduction in the rotational speed of the arc, which causes the arc column to extend in response to the cooling gas flow. The arc becomes inclined as it is drawn out in the axial direction, and the force acting on unit length of the arc column is reduced; correspondingly, elongation in the azimuthal direction causes rotation in the velocity vector such as to reduce the azimuthal component, so one has to bear in mind processes that control the arc elongation in order to account for the effects of the cooling gas at low flow rates, i.e., one has to incorporate the aerodynamic factor and the breakdown in the gas layer near the electrode.

The type of electric breakdown is unaltered at constant pressure, constant gas composition, and constant discharge-chamber geometry; the last is reflected by the number δ/D, while the gas composition and pressure remained unchanged in the experiments. The aerodynamic factor may be incorporated via the quantity $\Pi_6 = \rho_0 W^2/P$ or the equivalent one $\Pi_7 = W^2/h_0$; the following is the empirical formula applicable for the entire range of gas flow speeds when Π_7 is used:

$$\frac{U\delta\sigma_0}{I} = 0.967\left(\frac{\rho_0 h_0^2\sigma_0^2\delta^5 B}{I^3}\right)^{0.37}\left(\frac{\delta}{D}\right)^{0.379}\exp\left(-3.42\,W/\sqrt{h_0}\right).$$

This becomes (3) for W = 0, which shows that the last term has very little effect, and causes practically no change in the numerical coefficient and the powers; numerical estimates confirm this. In fact, at the maximal speed $W = 33$ m/sec, the factor $\exp(-3.42/\sqrt{h_0})$ differs from unity by only 1.5%, whereas the coefficient of variation in (8) is 11.4%, which is greater than for the simple formula (3). Therefore, it is best to use (3) for small gas flow speeds; for $\Pi_3 > 3 \cdot 10^{-3}$, one gets better accuracy from (2).

It is useful to check the effects of other quantities; in particular, it would be desirable to take into account conductive heat transfer within the arc column and convective transfer at its surface. This aspect is being studied, and the results will be published.

NOTATION

B	is the magnetic induction;
I	is the current;
$W = G/\rho^{F}_{x\,\mathrm{gap}}$	is the velocity of arc in the direction of electrode axis;
U	is the voltage;
D	is the diameter of external electrode;
δ	is the gap between electrodes;
σ_0	is the electric conductivity;
ρ_0	is the density;
h_0	is the enthalpy;
μ_0	is the magnetic permeability;
P	is the pressure;
$F = (\pi/4)[D^2 - (D - 2\delta)^2]$	is the area of gap between electrodes;
G	is the gas flow rate.

Subscripts

0	denotes the characteristic value;
x	denotes the cold gas at constant temperature.

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