EXPERIMENTAL STUDY OF AN ELECTRIC ARC MOVING IN AN ANNULAR VENTILATING GAP BY THE ACTION OF ELECTROMAGNETIC FORCES

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Formulas are derived for calculating the velocity of an electric arc in an annular ventilating gap under atmospheric pressure when an external magnetic field is applied, also for calculating the air density in front of the moving arc.

A formula for calculating the velocity of an arc in a magnetic field was proposed in [1]. After conversion to IS units, this formula becomes

$$v_0 = 21.5\cdot 10^{-3}\sqrt[3]{\frac{IH^2}{C_x^2\rho_0^2}}, \qquad (1)$$

where $C_x = 1 + 0.108H^{0.3}$. This and several other formulas in [3, 4] were obtained for the motion of an arc along a straight trajectory between parallel electrodes under conditions approaching those which prevail in arc quenching components of commutators.

Calculating the velocity of an arc in a coaxial plasmatron by formula (1) results, apparently, in a large error – the velocity of an arc in an annular interelectrode gap of a coaxial plasmatron may exceed the calculated value 2-3 times. Such a difference in velocities is due to different conditions under which an arc moves in a plasmatron and between parallel electrodes. The most important difference is that in a plasmatron the arc moves along a closed trajectory, passing many times through the same location in space. At a sufficiently high velocity, every time the arc completes another turn in air already heated up during the preceding turns, the density of that air has been reduced relative to the density of the oncoming unperturbed air stream, and this results in an arc velocity higher than calculated by formula (1).

Indeed, there are also other special conditions which prevail in the discharge chamber of a plasmatron. First of all, driven by the shunting mechanism, the arc moves along the chamber axis simultaneously

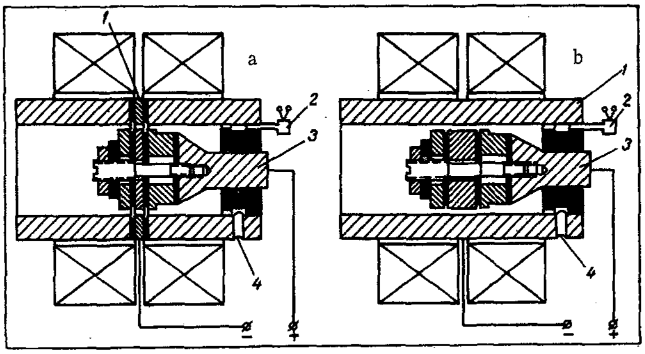

Fig. 1. Schematic diagram of the apparatus with segmented electrodes (a) and with solid electrodes (b): 1) outer electrode; 2) phototransmitter; 3) inner electrode; 4) air inlet hole.

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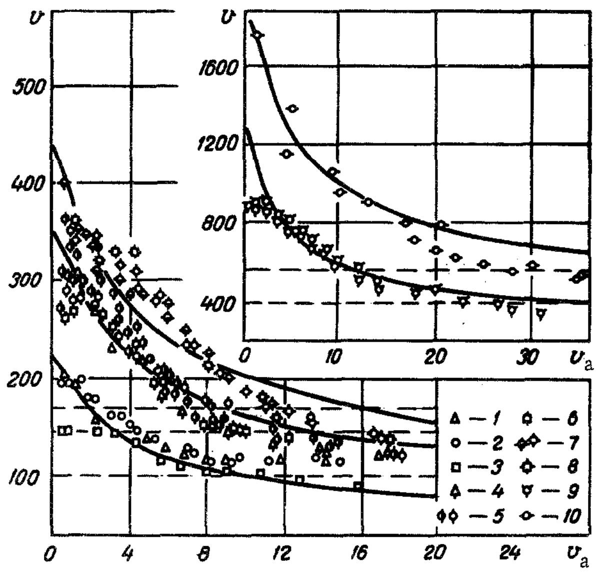

Fig. 2. Circular velocity of arc as a function of axial velocity of air. Data obtained using solid electrodes are marked by symbols filled in dark. Dashed lines indicate arc velocities calculated according to formula (1). The inner electrode was positive, the outer electrode was negative. $H = 1.06 \cdot 10^5$ A/m, I = 280 A, h = 3 mm (1); 5 mm (2); 7 mm (3); I = 833 A, h = 3 mm (4); 5 mm (5); 7 mm (6); I = 1330 A, h = 5 mm (7); 7 mm (8); $H = 7.5 \cdot 10^5$ A/m; I = 745 A; h = 5 mm (9); $H = 17 \cdot 10^5$ A/m; I = 756 A; h = 5 mm (10).

as it moves around a circle. Because of a powerful constriction of the gas stream in the arc zone, furthermore, there is a possibility of gas flowing in the radial direction. These circumstances are less significant, however, than the basic reason for the discrepancy between formula (1) and experimental results under plasmatron conditions, namely the difference between the actual gas density in front of the arc and the gas density in an unperturbed stream.

The effect which a displacement of the arc bearings due to shunting has on the peripheral velocity of the arc was established experimentally. For this purpose, the circular velocity of an arc was measured first in a system without shunting, the latter having been eliminated by the retention of both arc bearings on narrow ring sections (2.7 mm wide) by means of insulation (Fig. 1a), and then in a system where shunting took place owing to very wide electrodes (axial width of the outer electrode 150 mm, of the inner electrode 15 mm) (Fig. 1b). The experiment did not reveal any significant difference in the arc velocity under those two conditions (Figs. 2, 3), except that with wide electrodes the circular motion of the arc became less uniform in time – even though the average velocities during the time of recording (0.04-0.05 sec) remained approximately the same.

The arc velocity was measured with a phototransmitter containing an FD-1 photodiode [7]. Electric pulses generated by the arc appearing in the transmitter field of vision one every turn were recorded on a loop oscillograph with the loop operating at a frequency of 17 kHz, and at a sweep rate of 10 m/sec the arc velocity was determined as an average over the recording time.

The circular velocity of the arc was recorded with the phototransmitter as a function of the axial air velocity, of the current, of the magnetic field intensity, and of the interelectrode gap (Figs. 2, 3). At a constant current and magnetic induction, the circular velocity appears to vary by a factor of up to 2-3 as the axial air velocity changes. Moreover, at high values of v_a the arc velocity is almost as calculated by formula (1), while at lower values of v_a the arc velocity increases rather fast. An explanation for this could be that at high values of v_a the arc actually moves in cold air, since all the air around the arc orbit has time to be fully replaced during one turn of the arc, while at low values of v_a the arc enters a region of air already heated up during the preceding turns of the arc and thus having a lower density. A reduced air density in front of an arc causes the arc velocity to increase.

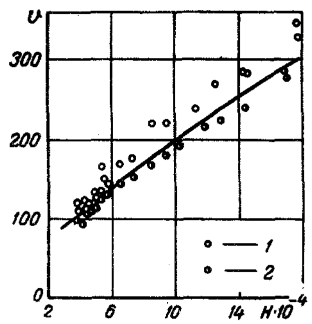

Fig. 3. Circular velocity of the arc as a function of the magnetic field intensity at I = 850 A, v_a = 5.28 m/sec, h = 5 mm; inner electrode positive: a) segmented electrodes; 2) solid electrodes.

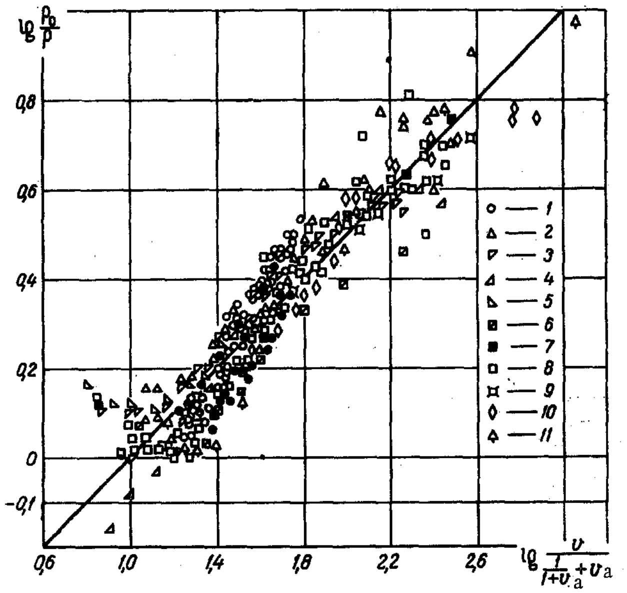

Fig. 4. Dimensionless gas density ahead of the arc, as a function of the axial air velocity to circular velocity of arc ratio. The symbols filled in black correspond to a negative inner electrode, the blank symbols correspond to a positive inner electrode. H = 1.06·10^5 A/m, segmented electrodes: h = 5 mm: 1) v_a = 5.28 m/sec, I = 150-1500 A; 2) v_a = 0.5-18 m/sec, I = 845 A; 3) v_a = 0.5-15 m/sec, I = 285 A; 4) v_a = 1-17 m/sec, I = 1320 A; h = 3 mm: 5) v_a = 0.7-14.5 m/sec, I = 295 A; 6) v_a = 0.8-17.5 m/sec, I = 1327 A; 7) v_a = 0.7-17.5 m/sec, I = 826 A; solid electrodes: h = 5 mm; 8) v_a = 0.6-17.5 m/sec, I = 845 A; 9) v_a = 0.6-12 m/sec, I = 1330 A; segmented electrodes: 10) H = 7.5·10^5 A/m, h = 5 mm, v_a = 0.6-31 m/sec, I = 802 A; 11) H = 17·10^5 A/m, h = 5 mm, v_a = 1.2-35 m/sec, I = 760 A.

For practical plasmatron design calculations it is very important to study the arc in motion pattern where it enters its own heat trail, since precisely this is what characterizes the operating mode of coaxial plasmatrons. This ensures the attainment of the maximum mean-mass-temperature in a plasmatron stream and offers the most favorable conditions for a reliable performance of the electrodes while, on the other hand, at high air velocities v_a one observes that the arc is "blown off" toward the end portion of the inner electrode often causing it to burn up. A coaxial plasmatron can operate reliably at high air velocities only when special arrangements are made for retaining the arc in the interelectrode gap.

In the experiments described here the axial air velocity was calculated from the equation of flow rate, in terms of density, at the inlet to the discharge chamber and from the area of the interelectrode gap. The rate of air flow was measured with critical flowmeters, the pressure in the discharge chamber was approximately 740 mm Hg, and the air temperature at the inlet was 10°C. The air density was assumed 1.22 kg/m^3 under these conditions.

The circular velocity of the arc was calculated from the number of turns per second and the mean diameter of the annular interelectrode gap:

$$v = \pi D_m f, \tag{2}$$

where $D_m = (D_c + D_a)/2$.

Not only the arc velocity but also the voltage drop across the arc was measured in all experiments. It was discovered here that, at a fixed arc length, the voltage drop across the arc changes very slightly as the axial air velocity varies over a wide range (0-20 m/sec) while the arc current and the magnetic field intensity remain constant. This suggests that a change in axial air velocity and, therefore, in the gas temperature ahead of the arc has almost no effect on the diameter of the arc column and on the electric field intensity within it. An explanation for this is, evidently, that any decrease of the heat dissipation due to higher temperatures of the surrounding air is compensated by an increase due to higher air velocity. We will note that in coaxial plasmatrons, where the arc length is adjustable, the voltage drop across it increases as the air velocity v_a increases, but this increase is apparently due to an increase of the mean arc length as a result of the axial displacement during shunting.

When the motion of the arc has become stable, the resistance force is equal to the driving force. The driving force is expressed by the product I × B, while the aerodynamic resistance may be evaluated by the formula:

$$F_R = C_x d \frac{\rho v^2}{2}, \tag{3}$$

if the arc is treated as a solid beam. This is entirely valid at pressures equal to or higher than atmospheric, since the gas in the column will now heat up to 10-12,000°K temperatures and its viscosity will be many times higher than that of the surrounding air at a few hundred to 1-2000°K temperature. Equation (1) was derived by G. A. Kukekov under this assumption. Precisely the same approach to analyzing the motion of an arc was taken in [5].

If the magnitudes of I and B are maintained constant, then the driving force remains constant too and, therefore, the equal to it aerodynamic resistance does not change. For two modes of arc motion with different air velocities v_a but the same I and B we can thus write

$$C_{x1}d_1\frac{\rho_1 v_1^2}{2} = C_{x2}d_2\frac{\rho_2 v_2^2}{2}. \tag{4}$$

If the value of v_a has no effect on the arc diameter, then

$$\rho_1 v_1^2 = \rho_2 v_2^2 \tag{5}$$

with the additional assumption that $C_{X1} = C_{X2} = \text{const.}$

The ratio of air densities in front of the arc for any two modes of arc motion with different air velocities can thus, at constant I and B, be expressed by the ratio of arc velocities.

If motion of the arc in an unperturbed air stream is chosen as one of these two modes, then (5) can be rewritten as

$$\rho v^2 = \rho_0 v_0^2 \tag{6}$$

or

$$\rho_0/\rho = (v/v_0)^2. \tag{7}$$

Relation (7) allows one to calculate the gas density ahead of the arc on the basis of its measured velocity (the values of v_0 and ρ_0 must be known here).

It would be most useful to obtain an expression relating the gas density ahead of the arc to the arc velocity v and the air velocity v_a. For this purpose, all experimental data pertaining to the arc velocity at different combinations of I, B, v_a, and h values were plotted graphically in terms of $\rho_0/\rho = f(v/v_a)$. As it turns out, all test points line up consistently enough on the single curve:

$$\lg\frac{v}{v_a} = 1 + 2\lg\frac{\rho_0}{\rho}. \tag{8}$$

The ratio ρ_0/ρ was calculated as $(v/v_0)^2$ according to (7). The value of v_0 was not determined by special experiments but was calculated according to Eq. (1), since this equation yields reliable results when the arc moves in unperturbed air and since it already has been confirmed by numerous experiments.

At low velocities, however, one observes a considerable dispersion of test points. This can be explained by the fact that equality (8) becomes invalid when $v_a \to 0$, since then $\rho \neq 0$. If now v_a is replaced by an empirical function of v_a, namely by $[1/(1 + v_a)] + v_a$, then the dispersion will become insignificant (Fig. 4).

As has been shown by experiment, equality

$$\lg\frac{v}{\dfrac{1}{1+v_a} + v_a} = 1 + 2\lg\frac{\rho_0}{\rho} \tag{9}$$

is satisfied also at $v_a = 0$. Equality can also be written as

$$\rho = \rho_0\sqrt{\frac{10\left(\dfrac{1}{1+v_a} + v_a\right)}{v}}. \tag{10}$$

Equalities (9) and (10), when supplemented by the G. A. Kukekov Eqs. (11) and (12) for the derivation of formula (1), allow one to obtain an expression for the velocity of an arc moving in an annular gap in an axial air stream.

Let us write an equation which expresses the fact that the driving force is equal to the aerodynamic resistance acting on the arc:

$$1.256 \cdot 10^{-6} IH = C_x d \frac{\rho v^2}{2} \tag{11}$$

and let us add here the empirical relation obtained by G. A. Kukekov between current density in the arc and velocity of the arc moving in air

$$j = 2v_0 \cdot 10^6 \tag{12}$$

or

$$\frac{2I}{10^6 \pi d^2} = v_0. \tag{13}$$

From the simultaneous solution of (6), (10), (11), and (13) one can obtain a formula for the arc velocity v in an annular gap, and one can express the other unknown quantities ρ, d, and v_0 in terms of the known ones ρ_0, I, H, C_x, and v_a:

$$v = 2.76 \cdot 10^{-3} \left(\frac{IH^2}{C_x^2 \rho_0^2} \right)^{\frac{4}{9}} \frac{1}{\sqrt[3]{\frac{1}{1+v_a} + v_a}}, \tag{14}$$

where $C_x = 1 + 0.108\,H^{0.3}$.

We will note that the gap width between electrodes does not enter into Eq. (14). Experiments have shown that the arc velocity is independent of the gap width, if the gap is over 3 mm wide (Fig. 2). Only at very narrow (~1.5 mm) gaps, not encountered in coaxial plasmatron designs, does one observe a mild velocity peak (at $H = 1.06 \cdot 10^5$ A/m).

The curves plotted according to Eq. (14) are superposed on the test points in Figs. 2 and 3. As is indicated by the diagram, there is a close agreement with experimental data even at arc velocities up to 1500 m/sec (when $v_0 \simeq 600$ m/sec).

If v_0 is found from Eqs. (6), (10), (11), and (13), then we arrive at the known G. A. Kukekov Eq. (1).

We will note that expression (13) is equivalent to the O. B. Bron equation for an arc diameter [2, 3]:

$$d = 0.8 \sqrt{\frac{I}{v_0}} \cdot 10^{-3}. \tag{15}$$

From the given system of equations, therefore, one obtains the same expression for the arc diameter as from Bron's Eq. (15) by inserting into it G. A. Kukekov's Eq. (1) ($\rho_0 = 1.24$ kg/m^3):

$$a = 5.8 \cdot 10^{-3} \sqrt[3]{\frac{IC_x}{H}}. \tag{16}$$

For the gas density ahead of the arc we have

$$\rho = 60 \rho_0^{13/9} \left[\frac{\left(\frac{1}{1+v_a} + v_a \right)^3 C_x^2}{IH^2} \right]^{2/9}. \tag{17}$$

Thus, at $v_a = 0.05$ m/sec, I = 1500 A, $H = 1.06 \cdot 10^5$ A/m, P = 1 bar, and $\rho_0 = 1.24$ kg/m^3 we have $\rho = 0.16$ kg/m^3, which corresponds to a temperature of about 2200°K.

NOTATION

v arc velocity, m/sec;
v_0 re velocity in an unperturbed air stream, m/sec;
v_a axial air velocity in the interelectrode gap, m/sec;
I current, A;
j current density, A/m^2;
B magnetic induction, T;
H magnetic field intensity, A/m;

F_R aerodynamic resistance, N/m;
C_x aerodynamic resistance coefficient;
D_c cathode diameter, m;
D_a anode diameter, m;
d arc diameter, m;
h interelectrode gap, m;
f circular frequency of arc motion, sec^{-1};
ρ air density ahead of the arc, kg/m^3;
ρ_0 air density in an unperturbed stream, kg/m^3.

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