SOME GENERALIZATIONS RELATING TO THE STUDY OF ELECTRIC ARCS

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§ 1. Stabilized Arcs in the Chambers of DC Plasma Generators

1°. It is known that an arc segment at right angles to the velocity vector of a flow of nonconducting gas will be entrained in the direction of flow [1]. The radial segment of the arc in plasma generators of the type shown schematically in Fig. 1 is exposed to similar conditions. However, as practice has shown, if the electrode 2 is sufficiently long, the arc does not go beyond the limits of the arc chamber and is not quenched. The reasons for this may be determined by making a study of the successive states of the arc.

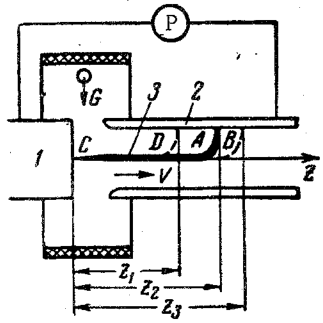

Fig. 1. Successive states of arc in arc chamber: 1 and 2) electrodes, 3) arc, P) power source, v) direction of motion of gas.

As it moves along the channel and the arc, the gas entering the arc chamber is heated, with the result that the diameter of the positive column centered on the z axis increases. However, owing to intense cooling of electrode 2, the positive column can not expand to the wall of the arc chamber; they always remain separated by a layer of practically nonconducting gas. In this zone there occur processes which play a decisive part in the mechanism that controls the length of the arc. The most important of these are ionization of the gas as a result of collisions with electrons accelerated in the electric field, particle excitation due to the high temperature, photoionization, and the excitation of neutrals due to radiation from the arc. All these factors considerably reduce the electric strength of the gas [2, 3] and create favorable conditions for breakdown between the positive column and electrode 2.

We shall conventionally take the potential of electrode 1 as zero. In this case the potential of electrode 2 will be equal to U_g. We denote the arc potential in an arbitrary fixed section z by $U_g(z)$. Then, in the section z, between the positive column and electrode 2 there exists a potential difference

$$\Delta U(z) = U_g - U_g(z) . \tag{1.1}$$

At a given moment let the arc spot be located at a "point" A. As the spot moves away from point A, the length of the arc and the potential of electrode 2 increase. Accordingly, $\Delta U(z)$ also increases. However, $\Delta U(z)$ can not increase without limit. As soon as the $\Delta U(z)$ at some section becomes equal to the breakdown potential, breakdown occurs between the positive column and electrode 2 and a new conducting channel is formed. Let us assume that breakdown occurs at the section z_1 when the spot is at point B. As a result of the formation of a new, shorter radial arc segment the former conducting channel, which lay between sections z_1 and z_3 and had greater electrical resistance, is suppressed. The newly formed radial segment is also entrained by the flow and when it reaches section z_3 breakdown (shunting) again occurs. It is these periodic breakdowns between the positive column and electrode 2 that limit the length of the arc.

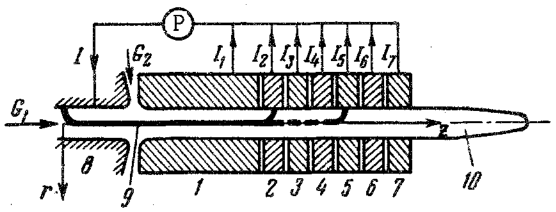

Fig. 2. Plasma generator with segmented cathode: 1)-7) cathode segments, 8) anode, 9) arc, 10) flow of heated gas, G_1), G_2) gas inlets, P) power source.

The arc shunting mechanism described was investigated on a plasma generator with a segmented output electrode-cathode, as shown schematically in Fig. 2. Figure 3 shows typical oscillograms of the currents I_5 and I_6 passing through two adjacent (fifth and sixth) segments of the 8-mm thick cathode. These oscillograms were recorded with a single double-beam OK-17M oscillograph. Just before the spot reaches the segments in question there are no currents. Then the current through the fifth segment abruptly increases (downward deflection of line I_5) to its maximum value. After a certain time the current I_5 through the fifth segment disappears, but then reappears in the sixth segment (upward deflection of line I_6). Finally, the current I_6 also disappears and after a certain interval (~ 75 μsec) the entire process is repeated.
In these experiments we simultaneously measured the instantaneous values of the currents through the six segments. Numerous oscillograms, similar to those presented in Fig. 3, showed that the cathode spot, moving in the direction of motion of the flow, passes successively from one segment to the other. When the spot has moved through a distance equal to the thickness of several segments, a new channel appears as a result of breakdown at the top of the flow (large-scale shunting). This is confirmed by the reappearance of the current on the oscillogram (Fig. 3). All this proves the above-mentioned hypothesis concerning the arc stabilization mechanism. Since the gas is a viscous medium, its velocity directly at the wall is zero. With distance from the wall the gas velocity increases. Accordingly, we may expect the arc

itself to be deformed in conformity with the velocity profile, i. e., to take the form of a loop, as shown in Fig. 4. In this case, so-called small-scale shunting of the loop is possible as a result of breakdown between points D and F. The mechanism of formation of a new channel and suppression of an old one is analogous to that described above.

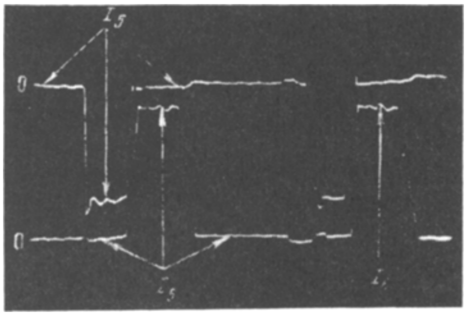

Fig. 3. Oscillograms of currents through the fifth and sixth segments. Sweep time 250 μsec, current 90 a, air flow rate 10. 2 g/sec.

The phenomenon of arc shunting in plasma generators with water stabilization of the arc was noted in [4]. Studies of arcs with gas stabilization, made independently by other authors using other methods, also point to the presence of the above-mentioned shunting mechanism [5-7].

In our experiments at a mean mass gas velocity of 850-900 m/sec the axial component of the cathode spot velocity, determined as the ratio of the segment thickness to the dwell time of the spot on the segment, was about 180 m/sec. This difference in the velocities is attributable to shunting of the loop (Fig. 4). A number of authors have observed a similar loop shunting effect in the case of arcs moving in flat channels [8].

The oscillograms presented show that the burning of a dc arc in the chamber of a plasma generator is a nonstationary process. Large-scale shunting causes a variation in the length of the arc and large-scale current and voltage pulsations. Moreover, the oscillograms revealed small-scale current fluctuations with a frequency of the order of 10^5 cps during the dwell time of the arc spot on the segment.

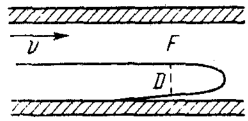

Fig. 4. Motion of radial segment of arc.

The pulsations of the flow parameters and the length of the arc lead to a certain statistical distribution of the breakdown frequency along the cathode. Accordingly, the current density (the ratio of the time-averaged current through the segment to the thickness of the segment) is distributed along the length of the channel in accordance with the graph shown in Fig. 5. The point z = 0 corresponds to the section in which the anode spot is located (Fig. 2). The graphs show that, other things being equal, the maximum and minimum arc lengths l_{max} and l_{min} decrease with increase in current. This is one of the reasons for the abrupt decrease in the potential drop across the arc with increase in current in ordinary plasma generators operating at relatively low currents. The experiments also showed that the nature of the distribution of the erosion of cathode material corresponds to the averaged current density distribution. Therefore it may be stated that for given arc and gas flow parameters cathode erosion is caused by the large heat fluxes through the cathode spot, and not by heat transfer from the flow of heated gas.

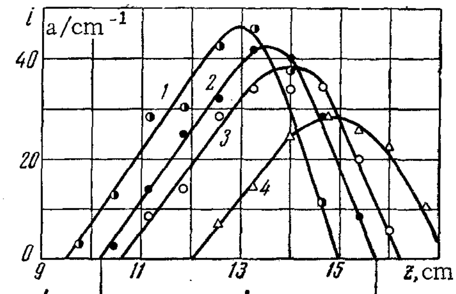

Fig. 5. Average current density distribution along length of cathode. Inside diameter of cathode 1 cm, G = 14 g/sec; curves 1, 2, 3, 4 correspond to values of the current I = 14. 7, 139, 127, 95 a.

Large-scale arc shunting leads to limitation of the potential drop across the arc. The potential drop cannot rise above this limit, even if the power source is capable of sustaining an arc with a higher potential drop. Thus, the power supplied to the flow and the temperature of the heated gas are limited by breakdown between the positive column and the arc chamber wall.

Let us consider a single-chamber plasma generator, in which the arc chamber is a cylindrical channel consisting of the cathode, an interelectrode insert, and an insulator. If the distance between electrodes a is small, i. e., $a < l_{min}$, the interelectrode insert has no effect on the arc burning conditions. We will call such electric arc heaters plasma generators with uncontrolled arc length, and denote by a_* the minimum length of the arc. If a is $> a_*$, then, by varying the dimension a, we can also regulate the minimum arc length over a certain interval. In this case a is one of the independent parameters determining the operating regime of the plasma generator. Depending on the function and design of the plasma generator, the interelectrode insert may take a variety of forms, e. g., it may be an insulator, a metal with a protective cold gas supply at the required point, or simply an interelectrode gap filled with gas, etc. When there is no insert, at sections $z < a_*$ it is possible to create breakdown conditions between the positive column and cathode artificially and to organize the burning of a shorter arc. In the general case the geometry of the cylindrical arc chamber is determined by two dimensions: a and d. Such plasma generators will be said to have an independent arc length. In [9, 10] the properties of the arc and the flow of heated gas were regulated by using an interelectrode insert. Variation of the length of the arc results in a qualitative and quantitative change in the arc characteristic. Thus, for example, for an argon flow of 0. 695 g/sec and d/a = 0. 221 the voltage-current characteristic of the arc forms an ascending branch, and the arc burns stably without a ballast resistance. However, at the same rate of flow of argon and d/a = 0. 695 the voltage-current characteristic forms a descending branch [10].

2°. Assuming that the pressure is close to atmospheric, we shall neglect the contribution of radiation to the energy balance of the arc [11]. The medium in the arc chamber is a mixture of molecules of the starting gas, newly formed molecules, atoms, ions, and electrons. The important parameters for the arc burning process, which determine the physical properties of the mixture, are as follows: the mass of the molecules of the starting gass m_a, the electron mass m_e, the masses of the newly formed molecules, atoms, and ions m_i ($i = 1, 2, \ldots, n$), the ionization potential of the starting gas U, the potentials of ionization, dissociation and excitation of the newly formed particles and molecules of the starting gas U_j ($j = 1, 2, \ldots, m$), the cross section for collisions of molecules of the starting gas and molecules of the same kind Q_a and electrons Q_{ae}, the cross sections for all other collisions Q_k ($k = 1, 2, \ldots, q$), the electron charge e, the specific heat of the starting gas c_v, and the magnetic permeability v. We shall specify the kinematics of motion of the gas by projections of its macroscopic velocity vector v_z and v_φ. In order to define the arc burning regime it is also necessary to specify the current I, the temperature of the inside wall of the channel T_R, the gas temperature at the inlet to the arc chamber T_b, the characteristic static pressure p, and the projections of the intensity vector of the external magnetic field H_z, H_φ, H_r. Neglecting the relatively small change in the cathode and anode potential drops U_k and U_a as a function of the current, we may include these too in the system of characteristic parameters. The work function of the electrons with respect to the electrodes φ is also an independent quantity and plays an important part in the mechanism of heat losses through the arc spot. If the dimension of temperature is taken as the primary dimension, then the system of characteristic parameters must also include the Boltzmann constant k. We shall assume that the length of the arc chamber is equal to the maximum length of the arc and is characterized by the two dimensions a and d.

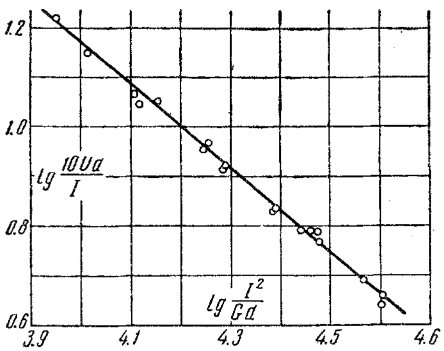

Fig. 6. Generalized current-voltage characteristic of arc in air.

Thus, the process is determined by (m + n + q + 23) independent quantities whose dimension can be constructed from the four primary dimensions. In accordance with the pi-theorem of dimensional analysis, from these quantities one can construct (m + n + q + 19) independent dimensionless power combinations.

We shall take the simplest of these combinations

$$\frac{m_e}{m_a}, \frac{m_i}{m_a} (i = 1, 2, \ldots, n), \frac{Q_{ae}}{Q_a}, \frac{Q_k}{Q_a} (k = 1, 2, \ldots, q), \frac{U_j}{U} (j = 1, 2, \ldots, m)$$

$$\frac{U_a}{U}, \frac{U_k}{U}, \frac{\varphi}{U}, \frac{eU}{kT_R}, \frac{v_z^2}{c_vT_R}, \frac{k}{c_vm_a}; \frac{I^2Q_{ae}a}{d^4v_ze^2p}(m_ekT_R)^{0.5}, \frac{\nu H^2}{p}, \frac{H_\varphi}{H_z}, \frac{H_r}{H_z}$$

$$\frac{dv_z\nu e^2}{Q_{ae}(m_ekT_R)^{0.5}}, \frac{dpQ_a}{kT_R}, \frac{kT_R}{ep^{0.5}d}, \frac{Q_a^{1.5}p}{kT_R}; \frac{T_b}{T_R}, \frac{v_\varphi}{v_z}, \frac{d}{a} \quad (1.2)$$

All the other dimensionless parameters characterizing the process in question are functions of the dimensionless combinations (1.2), which are the similarity criteria.

The dimensionless quantities (1.2) are different for different gasses, and therefore, in the general case, discharges in different gasses are not the same. Henceforth, we shall consider arcs burning in gasses of the same kind. In this case, the criteria

$$m_e/m_a,\ m_i/m_a,\ Q_{ae}/Q_a,\ Q_k/Q_a,\ U_j/U,\ k/c_vm_a$$

will be constant quantities and may be excluded from consideration.

Assuming that the processes in a plasma generator are described by a system of equations of magnetohydrodynamics and by the conditions for breakdown of the gas, we assign to the similarity criteria the forms obtained from an examination of these equations.

If we use the expression for the electrical conductivity

$$\sigma = e^2Q_{ae}^{-1}x(3m_ekT)^{-0.5},$$

we can represent the criterion $dv_z\nu e^2Q_{ae}^{-1}(m_ekT_R)^{-0.5}$ in the form $\sqrt{3}x^{-1}R_m$; here x is the degree of ionization of the gas, and R_m the magnetic Reynolds number.

The R_m number characterizes the influence of a moving conducting medium on a magnetic field [12]. It can be shown that

$$k(c_vm_a)^{-1} = \gamma - 1, \qquad v_z^2(c_vT_R)^{-1} = \gamma(\gamma - 1)M^2.$$

Here M is the Mach number, and γ is the ratio of specific heats.

The criterion $dpQ_a(kT_R)^{-1}$ is equal to the reciprocal of the Knudsen number K. Below we make use of a combination of the criteria

$$dpQ_a\ (kT_R)^{-1}, \quad m_a v_z^2\ (kT_R)^{-1}$$

in the form

$$dpQ_a\ (kT_R)^{-1.5}\ (m_a v_z^2)^{0.5},$$

which is proportional to the Reynolds number R.

If we express v_z in terms of the mass flow of gas per second G, then the criterion

$$I^2 Q_{ae} a\ (d^4 v_z e^2 p)^{-1}\ (m_e k T_R)^{0.5}$$

can be written in the form

$$c_1 I^2 a\ (Gd^2)^{-1}, \qquad c_1 = \pi m_a Q_{ae} m_e^{0.5}\ (kT_R)^{-0.5}\ (4e^2)^{-1}.$$

Using the expressions for the electrical conductivity and specific heat of the gas, we can show that this criterion is proportional to the ratio of the arc power to the internal energy of the mass flow G at the characteristic temperature T_R. The quantity $kT_R(ep^{0.5}d)^{-1}$ is proportional to the ratio of the Debye shielding distance to the channel diameter. The criterion $Q_a^{1.5}p(kT_R)^{-1}$ is equal to the ratio of the sum of the volumes of the gas molecules to the volume in which they are located. The remaining criteria are quite simple, and their physical significance is obvious.

3°. Analysis of the starting criteria (1. 2) shows that complete similarity of the arcs in chambers of different dimensions is impossible to realize. With the object of selecting dimensionless complexes taking into account only the most important integral energy properties of the arc and the flow, we shall reduce the number of criteria to a minimum, bearing in mind the special characteristics of arcs burning in plasma generators of the above-mentioned type. In this case we make the following assumptions.

(1) $R_m \ll 1$, i. e., the effect of the flow on the magnetic field may be neglected. For plasma generators this condition is satisfied with a high degree of accuracy. Thus, for example: $R_m = 1.11 \cdot 10^{-3}$ when $\sigma = 10^{13}$ sec^{-1}, $v = 10^5$ cm sec^{-1}, $d = 1$ cm, $\nu = 1.11 \cdot 10^{-21}$ sec^{2}cm^{-2}.

(2) The kinetic energy of the flow may be neglected as compared with its thermal energy. For example, for nitrogen at T = 7500°K and a velocity 10^5 cm/sec the kinetic energy of the flow is not more than 2% of its thermal energy.

(3) The gas is a perfect gas.

(4) The wall temperatures of the plasma generators compared are the same (usually the electrodes of plasma generators of the type in question are made of metal and, to prevent erosion, are strongly cooled; the electrode temperatures are below the melting point and vary only in a narrow interval).

(5) The gas temperatures at the inlets of the plasma generators compared are the same.

(6) Like electrodes of the plasma generators compared are made of the same materials and have the same terminal polarity.

(7) The effect of variation in Debye shielding distance on the energy balance of the arc may be neglected.

(8) For the plasma generators compared the condition $v_\varphi v_z^{-1}$ = idem is satisfied.

(9) There are no external magnetic fields.

When these conditions are satisfied, the criteria

$$U_a / U,\ U_k / U,\ eU / kT_R,\ T_b / T_R \text{ and } v_\varphi / v_z$$

degenerate into constants, while the criteria

$$R_m,\ kT_R\ (ep^{0.5}d)^{-1}, Q_a^{1.5}p\ (kT_R)^{-1}$$

may be discarded as unimportant.

Thus the dimensionless quantities characterizing the properties of the arc and the flow are functions of the criteria

$$K_1'' = \frac{c_1 a I^2}{d^2 G}, \quad K_2 = \frac{d}{a}, \quad R = c_2 \frac{G}{d}, \quad K = \frac{c_3}{dp}. \tag{1.3}$$

Here c_1, c_2, c_3 are dimensional constants. The dimensionless complex K_1'' in the form

$$f_1 = \pi d^2 b a E^2 (4 c_p G)^{-1}$$

was presented in [13]. Here $\sigma = bT_1$, T_1 is the temperature, and c_p the specific heat of the gas at constant pressure. It is easy to show that f_1 is only a modified form of K_1''

$$f_1 = \left(\frac{\pi d^2 b T_1 E}{4}\right)^2 \frac{4a}{\pi c_p T_1 G d^2 b} \sim \frac{I^2 a}{c_p b T_1^2 G d^2} = \frac{c' a I^2}{G d^2}.$$

In the special case when the geometry of the chamber is determined by the single dimension d, it is better to use the combination* of criteria K_1'' and K_2 in the form $K_1' = c_1 I^2 (Gd)^{-1}$.

Let us consider in more detail the case in which the Knudsen number is constant and the Reynolds number varies over a very narrow range. Analysis of the experimental material shows that in this case the arc characteristics are satisfactorily generalized with the aid of the criteria K_1' and K_2, i.e., the approximate similarity of the arcs is determined by the conditions K_1' = idem and K_2 = idem.

We write the dimensionless potential drop across the arc u_g in the form

$$u_g = \frac{U_g d}{I} \varepsilon, \qquad \varepsilon = \frac{e^2}{Q_{ae}} (m_e k T_R)^{-0.5}. \tag{1.4}$$

In accordance with our assumptions about T_R, the dimensional coefficients c_1 and ε are constant quantities. Therefore, the relation $u_g = u_g(K_1', K_2')$ may be replaced with the simpler expression

$$\frac{U_g d}{I} = f(K_1, K_2), \qquad K_1 = \frac{I^2}{Gd}. \tag{1.5}$$

Figure 6 presents the corresponding current-voltage characteristic for the data of [14].

It is clear from Fig. 6 that the generalized characteristic is quite well described by an expression of the form

$$\lg \frac{U_g d}{I} = \alpha - \beta \lg \frac{I^2}{Gd}. \tag{1.6}$$

The table presents values of α and β obtained from an analysis of the experimental material using the method of least squares.

Medium	α	β	θ	Type	d, cm	G, g/sec^{-1}	I, a
Air	3.500	0.853	—	1	1	1—3	100—300
Air	2.940	0.761	—	2	1	8—15	60—150
Air	2.792	0.655	—	3	1	8—15	60—150
Air	2.583	0.567	—	4	1	8—12	60—120
Argon	1.56	0.456	0.225	5	0.8	0.346—2.11	60—180

When the Reynolds number changes over a wide range, it is necessary to take into account its effect on the generalized characteristics of the arc. Thus, for example, analysis of the experimental data of [10] revealed the possibility of representing the generalized current-voltage characteristic, with allowance for the variation of R, in the form

$$\lg \frac{U_g d}{I} = \alpha - \beta \lg \frac{I^2}{Gd} - \theta \lg \frac{G}{d}.$$

The values of α, β, and θ are presented in the table. [Types of plasma generators: 1) single-chamber with special cathode spot stabilization; 2) two-chamber, subtractive polarity; 3) two-chamber, additive polarity; 4) two-chamber with interelectrode insert, K_2 = 0.057, additive polarity; 5) single-chamber with interelectrode insert, K_2 = 0.221, subtractive polarity].

*In [21], which appeared after the present article had gone to press, the criterion K_1' was obtained in a somewhat different form.

In our opinion, the effect of the Knudsen number on the properties of the arc should be investigated in greater detail. As is known from Paschen's work [2], the breakdown potential of a gas is a function of the Knudsen number. Therefore, the length of the arc, and also its other properties, must depend on this number. However, we still have no experimental data over a wide range of variation of the Knudsen number.

4°. We shall now consider the case in which the convective heat transfer may be neglected as compared with conductive heat transfer. Such arcs are realized in high-temperature plasma generators intended for research into the properties of plasma [15]. In this case practically all the energy supplied is carried away by ordinary radial heat conduction (Reynolds number small and no turbulent mixing), i.e., the arc is cylindrical. With account for the physical properties of the gas, the similarity criteria for a cylindrical arc with a low degree of ionization may be written in the form [16]

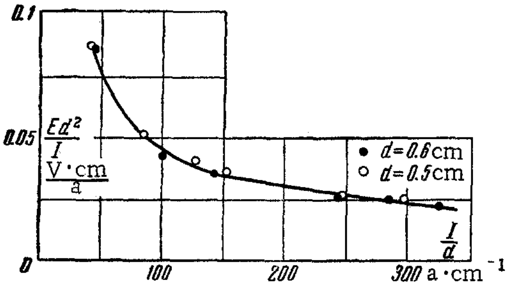

Fig. 7. Generalized current-voltage characteristic of arc in argon.

$$K_3 = \frac{\xi d^2 E^2 Q_a m_a^{0.5}}{Q_{ae} p^{0.5} T_R^{0.75}}, \qquad K_4 = \frac{U}{kT_R}. \tag{1.7}$$

Here ξ is a constant dimensional coefficient. Since the quantities T_R, E, and d are insufficient for the unique determination of the problem [17], in order to distinguish similar processes it is necessary to specify one more condition. This is the condition that the signs of dE/dI be the same for the processes compared. When arcs in gases of the same kind are studied, the constant dimensional quantities may be discarded, and the similarity condition will be

$$K_3' = d^2 E^2 p^{-0.5} = \text{idem}.$$

In this case the condition $Ip^{0.5}/Ed^2$ = idem is also observed; this follows from

$$I = 2\pi E \int_0^R \sigma r \, dr. \tag{1.8}$$

Therefore, the similarity condition may be specified in the form IE = idem or $Id^{-1}p^{0.25}$ = idem (in this case the condition T_R = idem is understood to be satisfied). A similarity condition in the form IE = idem is known from a number of studies [11].

Figure 7 shows the generalized current-voltage characteristic of the arc for small rates of flow of argon; the experimental points are taken from [15]. These points were obtained at the same chamber pressures; therefore in constructing the generalized characteristic pressure was not taken into account.

It should be noted that the generalization of the characteristics of arcs in inert gases without allowance for radiation is valid only for small values of the pressure, current, and channel diameter, since as these increase the part played by radiation become important.

§ 2. Motion of an Arc in a Magnetic Field

We shall briefly consider the application of similarity criteria (1.2) to the description of the properties of an arc moving in an undisturbed gas between parallel electrodes under the influence of a transverse magnetic field (Fig. 8). The difference between this problem and the preceding one consists in that in the given case the velocity of the arc relative to the medium and the velocity of the medium conditioned by the motion of the arc are parameters to be determined. Therefore the dimensionless combinations $v_z^2/c_v T_R$, v_φ/v_z must be eliminated from the system of criteria. The quantity v_z can be eliminated from the remaining criteria by multiplication or division by the complexes

$$v_z^2 / c_v T_R, \quad dv_z \nu e^2 (m_e kT_R)^{-0.5} Q^{-1}_{ae}.$$

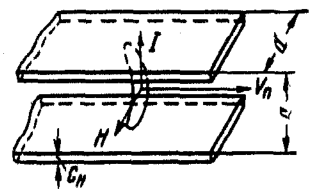

Fig. 8. Motion of arc between parallel electrodes.

We shall assume that the arcs compared burn in gases of the same chemical composition and that the conditions in the interelectrode space are such that the assumptions of § 1, except for assumption (9), hold true. Then the conditions of approximate similarity may be written in the form

$$K = \text{idem}, \quad \frac{I}{aH} = \text{idem},$$
$$\frac{\nu H^2}{p} = \text{idem}, \quad \frac{d}{a} = \text{idem}. \tag{2.1}$$

Here the criterion I/aH was obtained from the combination of dimensionless complexes (1.2) and is proportional to the ratio of the intrinsic magnetic field of the arc to the external magnetic field. The criterion I/aH may also be obtain directly from Maxwell's equations.

At a fixed temperature of the electrode surface the heat processes inside the electrodes have almost no perceptible effect on conditions in the interelectrode space. Moreover, the effect of the thickness of the electrodes, which is linked with the current distribution in them, is indirectly taken into account in the quantity H, since here H is the intensity of the magnetic field external in relation to the arc. Therefore the ratio a/c_H is not included amongst the criteria. The assumption concerning T_R imposes a constraint on the region of applicability of criteria (2.1): they are applicable only in the region where vaporization and melting of the electrodes may be neglected and where there are no metallic bridges between them. The dimensionless quantities characterizing the arc are functions of criteria (2.1).

We shall represent the dimensionless velocity of the arc V_n in the form $av_n\rho^{0.5}I^{-1}\nu^{-0.5}$. Figure 9 shows the dependence of the dimensionless velocity on the criterion $K_5 = I/aH$ for the data of [18]. The experiments described in [18] were carried out at atmospheric pressure and therefore a change in H leads to a change in the criterion vH^2/p. However, it is clear from Fig. 9 that in the given range of variation of I and H the dimensionless velocity depends only slightly on the criterion vH^2/p. Neglecting this weak effect, for K = const we can construct a single general dependence of the form

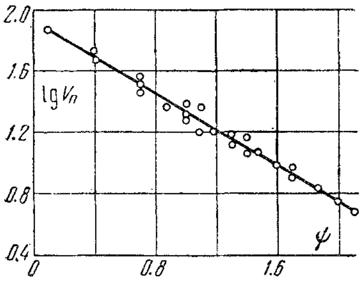

Fig. 9. Dependence of dimensionless velocity of arc on $\Psi = \lg 1000\, I/aH$

$$V_n = \varphi\left(\frac{I}{aH}\right). \tag{2.2}$$

If the field H is created by inductances connected in series with the arc, then the criterion I/aH for a = const degenerates into a constant quantity. Hence it follows that the current dependence of the arc velocity must be linear. This is well known from studies of arcing in switchgear [1]. As may be seen from the above, the establishment of this fact, on the basis of the theory of dimensional analysis, does not require any additional assumptions about the shape and dimension of the cross section of the arc and the current density distribution.

A more accurate formula for calculating V_n would take into account the dependence of V_n on the criterion vH^2/p and could be obtained by analyzing the same experimental material. However, on the basis of the considerations outlined above, it may be said that for approximate modeling of the arc velocity it is sufficient that the condition $I(aH)^{-1}$ = idem, da^{-1} = idem be satisfied. At present, we still have very little experimental material on the determination of the voltage of an arc moving in a magnetic field and certainly not enough for a generalization in criterial form.

§ 3. Free Arc

We shall assume that the arcs compared burn in an undisturbed gas of given composition and temperature T_R, the following conditions being satisfied:

(a) The pressure is close to atmospheric and the effect of radiation on the energy balance of the arc may be neglected.

(b) Like electrodes are made of the same material and the following condition is fulfilled:

$$d_k / a = \text{idem}, \qquad d_a / a = \text{idem},$$

where d_k and d_a are the cathode and anode diameters, and a is the interelectrode distance. Erosion of the electrodes may be neglected.

(c) The arcs are similarly oriented with respect to the force of gravity (g is the gravitational acceleration).

(d) There are no external magnetic fields.

Under these conditions the heat of the arc is dissipated by ordinary heat conduction and free convection conditioned by the arc itself; the effect of the convective fluxes on the intrinsic magnetic field may be neglected and the gas may be assumed perfect. The basic similarity criterion is taken in the form

$$I^2/a_{1.5}g^{0.5}\varkappa_R T_R,$$

Then the similarity conditions are as follows:

$$\frac{I^2}{a^{1.5}g^{0.5}\varkappa_R T_R} = \text{idem}, \qquad \frac{apQ_a}{kT_R} = \text{idem}. \tag{3.1}$$

Here $\varkappa_R$ is the heat conductivity of the starting gas at the temperature T_R. Conditions (3. 1) show that exact modeling of the arcs is not feasible. However, as shown by the analysis of a large number of current-voltage characteristics for arcs at atmospheric pressure, the criterion apQ_a/kT_R depends only slightly on the dimensionless potential drop.

Thus, for approximate similarity of the current-voltage characteristics the first of conditions (3. 1) must be satisfied.

We put the dimensionless potential drop across the positive column u_c in the form $U_c a^{0.5} g^{0.5}/I$, where $U_c = U_g - U_a - U_k$. Then we may write

$$u_c = u_c\left(\frac{I^2}{a^{1.5} g^{0.5} \varkappa_R T_R}\right) \qquad (3.2)$$

or, discarding the dimensional constants,

$$\frac{U_c a^{0.5}}{I} = f\left(\frac{I^2}{a^{1.5}}\right). \qquad (3.3)$$

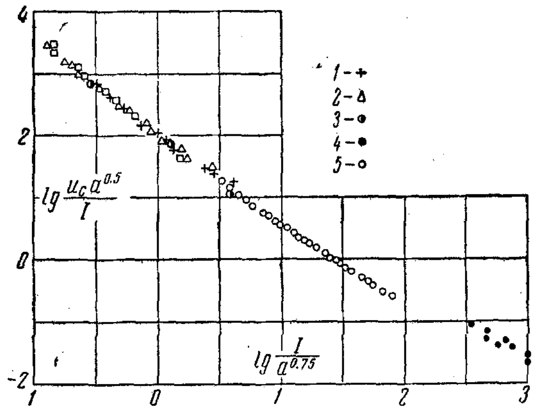

Fig. 10. Generalized current-voltage characteristic of free arc: 1) for I = 0. 5-7. 0 a, a = 2 cm, electrodes copper [19]; 2) for I = 0. 5-4. 5 a, a = 2-6 cm, electrodes iron [19]; 3) for I = 0. 55-6. 5 a, a = 2 cm, electrodes aluminum [19]; 4) for I = 200-750 a, a = 0. 35-0. 95 cm, cathode carbon, anode iron [20]; 5) data of G. Ayrton [11].

Figure 10 shows the generalized dependence of the potential drop across the arc based on a large number of ordinary current-voltage characteristics. This graph confirms the possibility of representing u_c in the form of a function of the similarity criterion $I^2/a^{1.5} g^{1.5} \varkappa_R T_R$. Since for $I^2/a^{1.5}$ = idem we have $U_c a^{0.5}/I$ = idem, the condition

$$\frac{I^2}{a^{1.5}} \frac{U_c a^{0.5}}{I} = \frac{I U_c}{a} = \text{idem}$$

must also be satisfied.

In other words, for similar free arcs the averaged (along the length) powers per unit length are the same.

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