PARTIAL SHUNTING OF AN ARC COLUMN BY STABILIZING DIAPHRAGMS

V. A. Baturin

The phenomenon of partial shunting of the column by the stabilizing diaphragm in a so-called "cascade" arc is examined. Experimental data on the dependence of this effect on the current, the thickness of the diaphragms, and the gas flowrate are presented for the case of an argon arc.

Arcs stabilized by cooled copper diaphragms are often used to obtain plasma for experimental purposes [1]. In these arcs the column plasma is in close contact with the conducting metal wall of the channel. Shunting of the arc by the wall is prevented by the fact that the stabilizing channel is divided into short, electrically insulated segments. However, the possibility of partial local shunting of the column by the walls of the individual diaphragms still remains. An analysis shows that the shunting current should depend on the nature and pressure of the working gas, the inside diameter and thickness of the diaphragms, the current and the electric field strength in the discharge column, and the nature and intensity of the gas flow in the stabilizing channel.

The electrical interaction of the column and the diaphragm walls was experimentally investigated in [2] for a weak-current arc in air at atmospheric pressure (the diameter of the stabilizing channel is not specified). At an arc current of 20 A and a diaphragm thickness of 15 mm the shunting current, according to measurements made by the authors of [2], was 5 mA. Nothing has been published on the shunting currents for arcs in other gases under different conditions.

We have investigated partial shunting in relation to the thickness of the diaphragms, the current, and the intensity of the axial gas flow in a stabilized argon arc ($p = 1$ atm) at a channel diameter of 5 mm.

1. In the "cascade" arc the shunting currents through the diaphragms are caused by the differences in distribution in the column and at the channel wall: the plasma potential V_p varies continuously along the z axis of the arc, whereas the potential of the segmented metal wall V_w has a stepwise variation (Fig. 1). Accordingly, radial potential differences $U_r(z) = V_p(z) - V_w(z)$, are established between the column plasma and the channel walls. It is assumed that within the thickness of each diaphragm there is a section $z = \text{const} = z_0$ (the z coordinate is reckoned from the left edge of the diaphragm), in which $V_w = V_p$ and hence $U_r(z)$ change sign: to the left of the plane z_0 they are directed from the column to the wall (are positive), to the right of the plane z_0 in the opposite direction (Fig. 1). We assume that the distribution of potential in the column $V_p(z)$ is linear, at least within the thickness of the diaphragm. Then, as may be seen from Fig. 1, the radial voltages

$$U_r(z) = \frac{dV_p}{dz}(z_0 - z) = E(z_0 - z) \tag{1.1}$$

Here, E is the electric field strength in the arc column.

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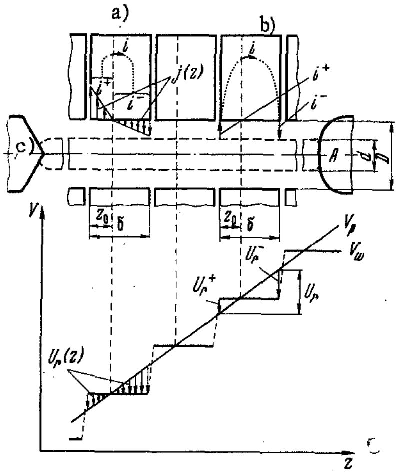


Fig. 1

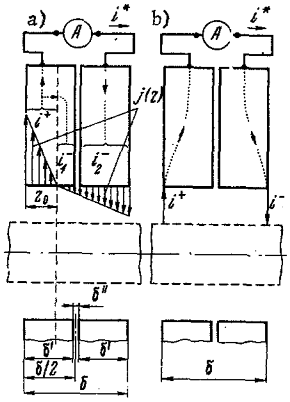


Fig. 2

In the presence of a finite boundary-layer resistance the radial voltage must produce radial currents closing across the diaphragm. These stray currents flow* from the column to the wall on the left of the diaphragm (cathode side of the plane z_0) and from the wall to the column on the right. We denote the total radial current flowing into the wall by i^+ and the reverse current by i^-. For an insulated (from the adjacent diaphragms) diaphragm

$$|i^+| = |i^-| = i \tag{1.2}$$

where i is the current flowing through the body of the diaphragm in the section formed by the plane $z = \text{const} = z_0$. Thus, each diagram partially shunts its own segment of the column, reducing the current through the plasma by an amount i (as compared with the current I at the electrodes).

We will consider two possible models of radial current flow through the boundary layer of gas: the distributed-contact and lumped-contact models. In the first case the radial stray currents are distributed over the entire inner wall of the diaphragm (Fig. 1a). Here we must introduce the concepts of a specific contact resistance ρ and a specific radial current j per unit length of channel. We denote the specific resistance to positive currents $j(z)$ (i.e., to currents due to the positive voltages $U_r(z)$ to the left of the plane z_0) by ρ^+ and the resistance to negative radial currents by ρ^-. The quantities ρ^+ and ρ^- are assumed to be constant (independent of z) for given conditions and a specific arc-burning regime. Since the positive and negative radial current flow processes are physically different [2], the values of ρ^+ and ρ^- must evidently be different. On the basis of certain experimental data [2] we may expect that $\rho^+ < \rho^-$. In this case in order to ensure the satisfaction of (1.2) the radial voltages $U_r(z)$ to the left of the section z_0 must on average be less than the voltages $U_r(z)$ on the right side of the diaphragm. Hence the plane z_0 must be located closer to the left edge of the diaphragm, as shown conventionally in Fig. 1.

In accordance with Ohm's law and using (1.1), the specific radial currents

$$j(z) = \begin{cases} U_r(z)/\rho^+ = (z_0 - z)E/\rho^+ & (0 \leqslant z \leqslant z_0) \\ U_r(z)/\rho^- = (z_0 - z)E/\rho^- & (z_0 \leqslant z \leqslant \delta) \end{cases} \tag{1.3}$$

where δ is the thickness of the diaphragm.

The total currents from the plasma to the wall and from the wall to the plasma are given by the expressions

$$i^+ = \int_0^{z_0} j(z)\,dz, \qquad i^- = \int_{z_0}^{\delta} j(z)\,dz \tag{1.4}$$

*Here the positive direction of the current is assumed to be the direction of motion of the electrons under the influence of the electric field.

Integrating (1.4) with allowance for (1.3) and using (1.2), we obtain

$$i = \frac{1}{2}\frac{E}{\rho^+} z_0^2 = \frac{1}{2}\frac{E}{\rho^-}(\delta - z_0)^2, \text{ or } \quad = c_1 \frac{E}{\rho^-}\delta^2 \quad \left(c_1 = \frac{1}{2}\left[1 - \left(\frac{z_0}{\delta}\right)^2\right]\right) \tag{1.5}$$

The ratio z_0/δ and hence the quantity c_1 are determined by the resistivity ratio ρ^+/ρ^-. Starting from the equation $z_0^2/\rho^+ = (\delta - z_0)^2/\rho^-$, contained in (1.5), it can be shown that

$$\frac{z_0}{\delta} = \frac{1}{1 + \sqrt{\rho^-/\rho^+}}, \quad c_1 = \frac{1}{2(1 + \sqrt{\rho^+/\rho^-})^2} \tag{1.6}$$

The second model presupposes that the stray currents i^+ and i^- are concentrated at the points of maximum radial voltage at the edges of the diaphragm (Fig. 1b). This form of column–diaphragm contact might be realized, for example, as localized semiself-maintained microdischarge through the boundary layer. We denote the resistances of the contact "bridges" at the left and right edges of the diaphragm by R^+ and R^- and the corresponding radial voltages by U_r^+ and U_r^-, respectively.

From Eq. (1.1) and Ohm's law

$$U_r^+ = U_r(0) = Ez_0, \quad U_r^- = U_r(\delta) = -E(\delta - z_0) \tag{1.7}$$

$$i^+ = \frac{U_r^+}{R^+} = \frac{E}{R^+} z_0, \quad i^- = \frac{U_r^-}{R^-} = -\frac{E}{R^-}(\delta - z_0) \tag{1.8}$$

If the diaphragm is completely isolated from its neighbors, we get a series stray-current circuit (from plasma to diaphragm wall and from wall to plasma) with overall resistance $R = R^+ + R^-$ and effective voltage

$$U_r = |U_r^+| + |U_r^-| = E\delta \tag{1.9}$$

Then the shunting current

$$i = \frac{U_r}{R} = \frac{E}{R}\delta \tag{1.10}$$

These two models lead to different relations between shunting current and diaphragm thickness: for distributed contacts $i \sim \delta^2$, whereas for lumped contacts $i \sim \delta$ (see (1.5) and (1.10), respectively). In order to establish which model is the more realistic, it is necessary to know the actual nature of the dependence of i on δ.

2. The shunting currents were experimentally determined on a stabilized argon arc [1] with channel diameter D = 5 mm. On one of the diaphragms there was a radial window for optical observations. The argon was fed to the arc from the cathode end.

We measured the arc current I, the electric field strength in the arc column E, the luminous diameter of the column d, the gas flowrate q, and the shunting currents i. The field strength E was found from the the energy balance of the column (at low argon flowrates) and from the potential distribution in the arc measured using the diaphragm as electric probes. The column diameter d was estimated from the size of an image of the column on a screen adjacent to the arc. Small gas flowrates were determined and monitored in relation to the pressure drop at a calibrated capillary, higher rates with the aid of RS-3 and RS-5 rotameters.

For detecting and determining the shunting currents we used a simple measuring circuit composed of two adjacent diaphragms of the same thickness δ' shorted across an ammeter (Fig. 2a, b). The resulting coupled diaphragm of thickness $\delta = 2\delta' + \delta''$ (δ'' is the gap between the two diaphragms) is equivalent with respect to electrical interaction with the arc column to a continuous diaphragm of the same thickness δ (provided that $\delta'' \ll \delta$).

If it is assumed that the radial currents are formed in accordance with the distributed-contact model, then when $z_0 < \delta/2$ the current i^* registered by the ammeter should be somewhat less than the total shunting current i (see Fig. 2a). The measured current is given by the expression

$$i^* = |i^+| - i_1^-| = |i_2^-| = \int_{\delta/2}^{\delta} j(z)\,dz \tag{2.1}$$

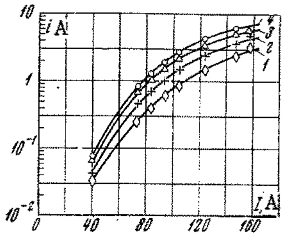


Fig. 3

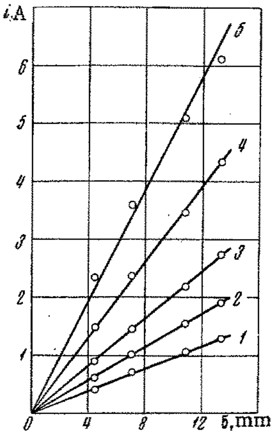


Fig. 4

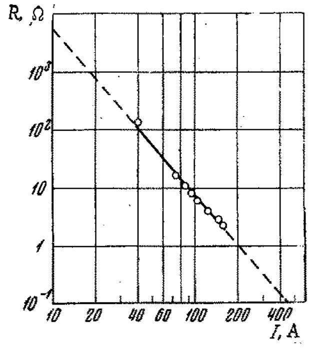


Fig. 5

Integrating (2.1) with allowance for (1.3), we obtain

$$i^* = \frac{E}{\rho^-}\left(\frac{3}{8}\delta^2 - \frac{1}{2}\delta z_0\right), \quad \text{or} \quad i^* = c_2\frac{E}{\rho^-}\delta^2 \quad \left(c_2 = \left[\frac{3}{8} - \frac{1}{2}\left(\frac{z_0}{\delta}\right)\right]\right) \tag{2.2}$$

Comparing (2.2) with (1.5) at various values of z_0/δ, we find that the current ratio i^*/i should lie on the interval ~0.75-1.0 (the least value of $i^*/i = 0.75$ corresponds to the case when $\rho^+ \ll \rho^-$ and, in accordance with (1.6), $z_0/\delta \to 0$).

Thus, we have shown that, when the distributed-contact model holds, the current i* registered by the instrument almost corresponds (both with respect to the nature of its dependence on δ and in magnitude) to the shunting current i in the continuous diaphragm.

If the lumped-contact model is correct, then, as is clear from Fig. 2b, all the shunting current flows through the ammeter, i.e., i* = i or, using (1.10),

$$i^* = \frac{E}{R}\delta \tag{2.3}$$

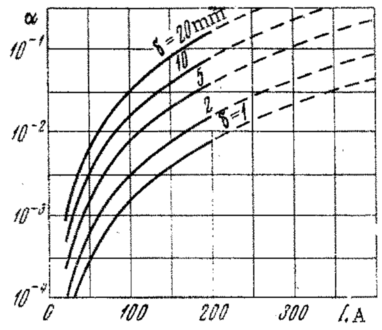
In view of the perfect coincidence of the currents i* and i in the lumped-contact variant and their near-equality in the distributed-contact variant we may approximately assume that i* = i irrespective of which model is valid. Accordingly, we shall henceforth drop the asterisk used to denote the measured shunting current.

To determine the nature of the dependence of i on δ, the shunting currents were measured on coupled diaphragms of different thickness arranged one behind the other in the same assembly as part of another device. These measurements were made at a low argon flowrate (q = 0.05 g/sec) in order to ensure the uniformity of the column [3] and thereby eliminate the effect on the currents i of the distribution of the diaphragms along the length of the channel.

The results of the measurements are presented in Fig. 3. Here, curves 1, 2, 3, and 4 describe the points obtained at diaphragm thicknesses δ = 4.5, 7.1, 10.8, 13.4 mm, respectively.

It is clear from Fig. 3 that the shunting currents are highly dependent on the arc current. Thus, at δ = 7.1 mm, as the current I increases approximately from 40 to 157 A (by approximately a factor of four), the current i increases from 0.044 to 4.75 A (i.e., by a factor of more than 100). This sharp dependence indicates that the arc current has a strong influence on the contact resistances. The latter should be determined by the thickness and state of the boundary layer. According to experimental estimates of the column diameter d, the thickness of the boundary layer δ* = 0.5(D − d) varied very considerably with variation of the arc current.

In Fig. 4 the measured currents i have been plotted against the diaphragm thickness δ. The experimental points are quite well fitted by straight lines drawn from the origin (curves 1-5 correspond to arc currents of 84, 94, 104, 124, and 147 A, respectively).



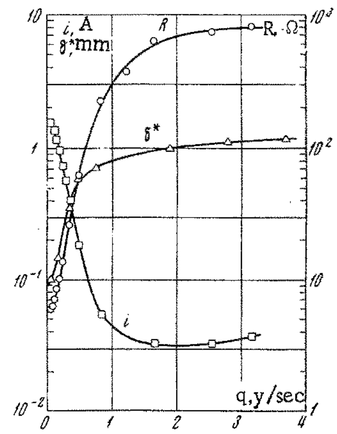


Fig. 6

Fig. 7

The linearity of the dependence of i on δ indicates that of the two models considered above the more probable is the lumped-contact model (Fig. 1b), which also leads to a linear dependence of i on δ (1.10). On the other hand, the distributed-contact model, according to which $i \sim \delta^2$ (1.5), clearly does not reflect the actual i-δ dependence. Thus, for the purpose of the subsequent analysis we shall employ the lumped-contact model and the corresponding equation (1.10).

Knowing δ and the experimentally measured values of i and E, from (1.10) we can determine the overall contact resistance R. In this case it is convenient to take the ratio i/δ from the slope of the approximating straight lines (Fig. 4). The values of R thus calculated have been plotted against the arc current I in logarithmic coordinates in Fig. 5. The points obtained are satisfactorily described by a straight line of the form

$$\lg R = \ln A + n \lg I \tag{2.4}$$

at values of $A \approx 4.0 \cdot 10^6$ and $n \approx -2.86$. Hence

$$R = AI^n \approx 4.0 \cdot 10^6 I^{-2.86} \tag{2.5}$$

Thus, the contact resistances are inversely proportional to the third power of the arc current. After substituting (2.5) in (1.10) we obtain the following expression for the shunting currents

$$i \approx 2.5 \cdot 10^{-7} \delta E I^{2.86} \tag{2.6}$$

The values of the current i calculated from this expression are within 20% of the measured values.

Expression (2.6) can also be written in the form

$$\alpha \approx 2.5 \cdot 10^{-7} \delta E I^{1.86} \tag{2.7}$$

where $\alpha = i/I$ is the shunting ratio.

It should be kept in mind that expressions (2.5), (2.6), and (2.7) were obtained for quite specific conditions in the arc (D = 5 mm, q = 0.05 g/sec, p = 1 atm).

The value of α was calculated from (2.7) for diaphragm thicknesses δ = 1, 2, 5, 10, and 20 mm on the arc current interval from 20 to 400 A. The values of the field strength E were taken directly from experiment on the current interval from 20 to 200 A and from the extrapolation of the experimental E(I) curve for currents I = 200–400 A. The results of the calculations are presented graphically in Fig. 6.

These calculations can be used to estimate the required thickness of the stabilizing diaphragms. Thus, for example, given $\alpha \leqslant 2\%$ and $I \leqslant 150$ A, according to Fig. 6, the thickness of the diaphragms should not exceed 5 mm.

The effect of the axial gas flow on the shunting process is illustrated in Fig. 7, where we have plotted i and R against the gas flowrate q using the data of measurements on a coupled diaphragm of thickness

$\delta = 8.1$ mm. The same figure shows the dependence of $\delta^* = 0.5(D - d)$ on q obtained on the basis of experimental estimates of the column diameter d by the method described. The measurements were made at a constant arc current $I = 100$ A.

As may be seen from Fig. 7, increasing the argon flowrate from 0.05 to 1.5 g/sec leads to a decrease in shunting current i approximately from 1.5 to 0.03 A (by a factor of about 50). After passing through a minimum (at $q \approx 2$ g/sec) the shunting current begins to increase slightly. This behavior can be explained as follows.

As the gas flowrate increases, the periphery of the arc column is more and more strongly cooled. As a result the thickness of the "cold" boundary layer significantly increases, especially in the region $0.05 < q \leqslant 0.5$ g/sec (Fig. 7). In these circumstances the column–wall contact resistance increases very sharply. This causes a sudden drop in the radial stray current despite the fact that as q increases there is a substantial increase in the field strength E (and thus the effective voltage U_r (1.9)). The latter factor begins to play a significant role only after the R(q) curve reaches "saturation." This occurs in the region $q \geqslant 2$ g/sec, where the i(q) starts to turn upward.

As q increases from 0.05 to 3.2 g/sec, the overall contact resistance R increases approximately from 6 to 800 ohm (by a factor of about 130), the thickness of the boundary layer δ^* approximately from 0.1 to 1.2 mm (by a factor of about 12). The stronger increase in R as compared with δ^* may be attributable to a fall in the mean temperature of the boundary layer T^* as q increases (obviously the gas flowrate affects the heat transfer mechanism, thus the radial temperature distribution near the wall and hence T^*).

One means of increasing the plasma temperature in the arc column is to increase the current I. The above experimental data and calculations indicate that in the case of an argon arc at low gas flowrate the possibility of increasing the current I is seriously limited owing to the strongly increasing shunting ratio. Thus, according to calculations based on (2.7), for diaphragms 5 mm thick the shunting ratio is about 3% at $I = 200$ A, about 10% at $I = 300$ A, and about 20% at $I = 400$ A (see Fig. 6). Moreover, as experiments have shown, a strong increase in the shunting ratio α disturbs the stability of the arc. An extreme increase in α may also lead to the destruction of the copper diaphragms (especially the right cathodic edges).

This constraint is practically eliminated at elevated flowrates, since in this case the shunting current is very sharply reduced (Fig. 7).

The data obtained may also prove useful in certain other respects. For example, a knowledge of the contact resistance is required in selecting the circuit for measuring the potentials and field strength in the arc column by means of diaphragm probes [2]. At high shunting ratios (for example, in the case of a heavy-current argon arc at low flowrates) a knowledge of α makes it possible to introduce a correction for the current measured in the external circuit of the arc. It is desirable to introduce such a correction in connection with certain quantitative investigations of the arc (for example, in determining the plasma conductivity).

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