ANALYSIS AND GENERALIZATION OF CURRENT—VOLTAGE CHARACTERISTICS OF DIRECT-ACTION PLASMATRONS

P. F. Bulanyi, S. P. Polyakov,
and M. G. Rozenberg

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The current—voltage characteristics of direct-action plasmatrons operating with air, nitrogen, or argon are analyzed and generalized.

Many studies have been made [1-8] of direct-action plasmatrons used for cutting metals, for plasma-arc smelting, for plasmomechanical processing, and for rotary extrusion with plasma heating. The principal parameters in most of these processes are the integral thermal flux and the specific thermal flux into the metal, both determined primarily by the current—voltage characteristic of the direct-action plasmatron and by the position of the latter relative to the processed object constituting the anode. This is suggested by the fact that the coefficient of effective heat transfer here varies within the 0.4-0.65 range [8]. So far, however, no generalization of the current—voltage characteristics of direct-action plasmatrons has been made, these characteristics intricately depending on electrical as well as gasdynamic parameters of the electric arc which, in turn, intricately depend on the design of the arc chamber (diameter and length of the nozzle, distance from the throat of the plasmatron nozzle to the cathode, etc.). The object of this study was an experimental determination and subsequent generalization of the current—voltage characteristics of direct-action plasmatrons operating under atmospheric pressure and using air, nitrogen, or argon as the plasma generating gas.

Attempts to generalize the current—voltage characteristics of the entire arc of a direct-action plasmatron in a criterial form or in a complex form without subdividing the arc into segments have been futile, because of the large number of independent parameters. Better results have been obtained by subdividing the electric arc into two segments (segment I from the cathode to the throat of the plasmatron nozzle and segment II from the throat of the plasmatron nozzle to the anode surface) and generalizing the current—voltage characteristics on that basis. The current—voltage characteristics on both segments are, respectively, ascending and descending in all plasmatron operating modes under consideration. The trend of the current—voltage characteristic of the entire arc is determined by the sign of the sum of derivatives $dU/dI = dU_I/dI + dU_{II}/dI$ at each value of the arc current. Accordingly, these authors deemed it correct to generalize the voltage drop across each segment and to calculate the resultant voltage across the electric arc as the sum of those voltage drops.

With the aid of the electric circuit shown in Fig. 1, we recorded I, V, and V_1 by tracing the signals on a model N-117 light-beam oscillograph. The potential V_1 was measured by the conventional method [9] with an electric probe in the form of a tungsten wire 0.3 mm in diameter cuting across the electric arc at the velocity of 1 m/sec. The resistor R_3 was 410 kΩ, it had been selected on the basis of data in another study [10]. The correctness of measurements was checked with a voltage probe along the segment from the throat of the plasmatron nozzle to the cathode. For this purpose, the probe was twice inserted into the arc under the same operating conditions. During the first cutting through the arc column was measured the voltage drop across the segment from cathode to nozzle throat; during the second cutting was measured the voltage drop across the segment from nozzle throat to anode. The sum of both voltage drops was found to be equal to the voltage across the entire arc, within the limits of measurement error (±2%). A steel shaft 120 mm in diameter rotating at 110 rpm served as the anode. Insertion of a smoothing filter F into the arc supply circuit reduced the ripple of the supply current to 4%. The variation of the arc length (distance $L_0 = L/\cos\alpha + h$) due to wobble of the rotating processed part did not exceed ±1%.

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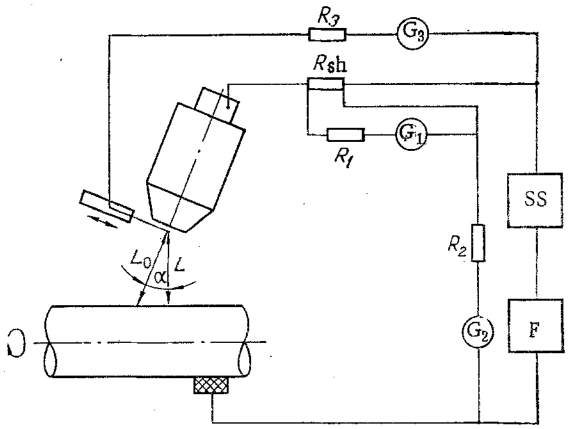

Fig. 1. Schematic diagram of measurements: SS) supply source; F) filter; G_1, G_2, G_3) galvanometers for recording the current and the voltage drops across the arc and across the segment from cathode to nozzle throat, respectively; R_1, R_2, R_3) external auxiliary resistors; R_{sh}) shunt resistor.

The parameters determining the arc performance were varied as follows: N from 18 to 65 kW, I from 80 to 400 A (during operation with nitrogen or argon), I from 80 to 320 A (during operation with air), G from $0.5 \cdot 10^{-3}$ to $2.5 \cdot 10^{-3}$ kg/sec, L_0 from $2 \cdot 10^{-2}$ to $10 \cdot 10^{-2}$ m, α from 0 to 60°, h from $4 \cdot 10^{-3}$ to $14 \cdot 10^{-3}$ m, and $d = (3, 4, 5, 6, 8) \cdot 10^{-3}$ m. The angle α in these experiments was in planes passing through the axis of the processed part. The cathode, $5 \cdot 10^{-3}$ m in diameter, for operation with nitrogen or argon was made of thoriated grade VT-10 tungsten and pressed into a water-cooled copper jacket. This tungsten cathode, sharpened to a point with a 90° opening angle, protruded $1 \cdot 10^{-2}$ m beyond the jacket. The zirconium cathode was of the conventional construction [11]. Some typical current—voltage characteristics of direct-action plasmatrons with various I, G, d, and h are shown in Fig. 2a-c. Depending on the arc parameters, these current voltage characteristics are continously descending, continuously ascending, or have both descending and ascending segments.

The method of dimensional complex groups was used for generalizing the current—voltage characteristics on both segments. For generalizing the current—voltage characteristics on segment I the general form of the expressions [9] was used

$$U_I = A\left(\frac{I^2}{Gd}\right)^m \left(\frac{G}{d}\right)^n (pd)^q \left(\frac{h}{d}\right)^r . \tag{1}$$

One can regard $(pd)^q$ as a constant quantity and incorporate in it the factor A. Indeed, [12], the pressure in expression (1) is that at the exit section of the nozzle, equal to $0.98 \cdot 10^5$ N/m² under the conditions of the experiment and not varied during the measurements. Consequently, the pd-complex thus becomes a d-complex. Furthermore, with the nozzle diameter in the direct-action plasmatron varied over a narrow range (through a factor of 2.66 only) and the numerical value of q much smaller than unity, it has been found possible not to enter the pd-complex in an explicit form.

TABLE 1. Values of Coefficients A, B, C and Exponents m, n, r, x, y, z in Expressions (1)-(3)

Plasma generating gas	A	B	C	m	n	r	x	y	z	q
Air	0,75	160	210	0,2	$0{,}356-1{,}2\,d$	0,50	0,27	$5{,}4\,\frac{L}{\cos\alpha}-38\,G$	0,55	0
Nitrogen	0,25	65	210	0,23	$0{,}5-50\,d$	0,75	0,16	$4{,}7\,\frac{L}{\cos\alpha}-$ $-65\,G+0{,}035$	0,64	0
Argon	0,306	38	210	0,2	$0{,}504-38\,d$	0,75	0,22	0,13	0,86	0

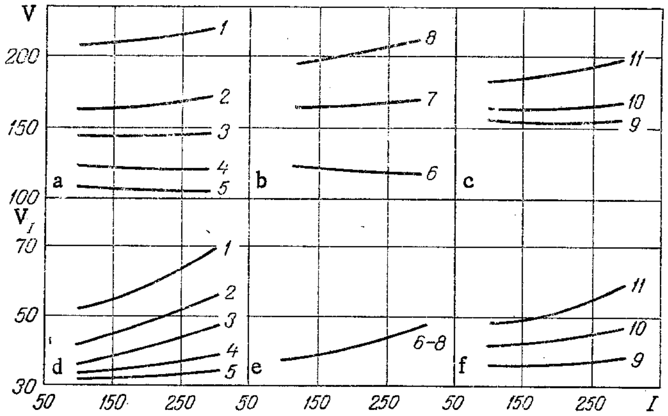

Fig. 2. Dependence of the voltage drop across the arc V (volts) (a, b, c) and of the voltage drop across the segment from cathode to nozzle throat V, (volts) (d, e, f) on the current I (amps): (a), (d) $G = 1.27 \cdot 10^{-3}$ kg/sec, 1-5) L = ?, nozzle diameter $d = (3, 4, 5, 6, 8) \cdot 10^{-3}$ m, respectively; (b), (e) $G = 1.27 \cdot 10^{-3}$ kg/sec, $d = 4 \cdot 10^{-3}$ m, 6-8) distance to the processed part $L = (30, 60, 90) \cdot 10^{-3}$ m, respectively; (c), (f) $L = 60 \cdot 10^{-3}$ m, $d = 4 \cdot 10^{-3}$ m, 9-11) air flow rate $G = (0.54, 1.27, 2.47) \cdot 10^{-3}$ kg/sec.

An evaluation of the experimental data (some of them shown in Fig. 2d-f) indicates that curves plotted on the basis of expression (1) agree with them within ±10%. The values of coefficient A and exponents m, n, r obtained experimentally are given in Table 1. The correspondence between experimental results and theoretical results based on calculations according to expression (1) is shown in Fig. 3d-f.

The current—voltage characteristics on segment II were generalized by the method shown in the earlier study [13]. Here the voltage drop V_{II} was experimentally determined as the difference between that across the entire arc and that across segment I. In the search for a generalizing expression we used some results of another study [10], where it had been demonstrated that the electric field intensity in the open part of the arc increases with increasing flow rate of the plasma generating gas but decreases with increasing arc current and increasing plasmatron diameter. In addition, we have also taken into account that the cross section of the electric arc tapers less as the distance from plasmatron nozzle to processed part is increased. The current—voltage characteristics on segment II were generalized in the form

$$U_{II} = BG^x \left(\frac{C}{I}\right)^y \left(\frac{L}{d\cos\alpha}\right)^z . \tag{2}$$

An evaluation of the results has established that the exponent y is a function of the gas flow rate and of the distance to the surface of the processed part constituting the anode. The values of coefficient B, C and exponents x, y, z are given in Table 1. The experimentally obtained values differ by not more than ±10% from those calculated theoretically on the basis of expression (2) and given in Table 1. The generalized equation of the current—voltage characteristics for a direct-action plasmatron operating with various plasma generating gases (air, nitrogen, argon) is

$$U = A\left(\frac{I^2}{Gd}\right)^m \left(\frac{G}{d}\right)^n \left(\frac{h}{d}\right)^r + BG^x \left(\frac{C}{I}\right)^y \left(\frac{L}{d\cos\alpha}\right)^z . \tag{3}$$

The experimentally obtained values differ by not more than ±20% from those based on expression (3). The correspondence between expression (3) and experimental data is shown in Fig. 3a-c.

The results of this study facilitate 1) the engineering design of direct-action plasmatrons and 2) selection of the plasmatron operating mode as well as setting the proper distance to the processed part.

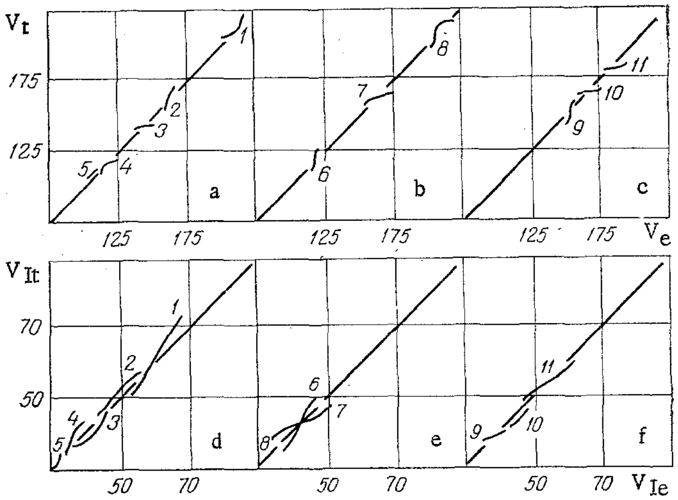

Fig. 3. Correspondence between experimentally determined voltage drops across the arc V_e (volts) and across the segment from cathode to nozzle throat V_{Ie} (volts) and those calculated theoretically V_t (volts) and V_{It} (volts), respectively, on the basis of expressions (3) and (1) for the same operating conditions as in Fig. 2.

NOTATION

V (volts), voltage drop across the arc; V_I (volts), voltage drop across the arc segment from cathode to nozzle throat; V_{II} (volts), voltage drop across the arc segment from nozzle throat to anode; I (A), arc current; L_0 (m), arc length; L (m), distance from the center of the nozzle throat to the anode; α (deg), angle between the plasmatron axis and the normal to the surface of the processed part, at the intersection of both; h (m), distance from the throat of the plasmatron nozzle to the cathode; N (kW), arc power; G (kg/sec), flow rate of the plasma generating gas; and d (m), diameter of the plasmatron nozzle.

LITERATURE CITED

1. D. G. Bykhovskii, Plasma Cutting [in Russian], Mashinostroenie, Leningrad (1972).
2. K. V. Vasil'ev, Plasma-Arc Cutting [in Russian], Mashinostroenie, Moscow (1974).
3. V. I. Lakomskii, Plasma-Arc Smelting [in Russian], Tekhnika, Kiev (1974).
4. A. N. Stroshkov, Sh. L. Tesle, S. P. Shabashov, and D. S. Élinson, Treatment of Difficult-to-Process Material by Cutting with Heating [in Russian], Mashinostroenie, Moscow (1977).
5. S. S. Kravchenko, V. S. Él'kin, M. L. Uritskii, et al., "Shaping of parts with plasma heating," in: Abstr. Proc. Eighth All-Union Scientific-Industrial Conf. "El'fa-77" on Electrophysical and Electrochemical Processing Methods, I. I. Polzunov Central Institute of Boilers and Turbines [in Russian], Leningrad (1977), pp. 188-189.
6. D. I. Vainboim and Zh. V. Ratmanova, "Energy characteristics of an arc in argon with various degrees of compression," Svarochn. Proizvod., No. 5, 1-3 (1974).
7. V. S. Éngel'sht and Zh. Zheenbaev, "Electric arc in the approximation of a laminar MHD boundary layer," in: Theory of an Electric Arc Under Conditions of Forced Heat Transfer [in Russian], Nauka, Novosibirsk (1977), pp. 32-49.
8. G. A. Farnasov, L. G. Fridman, and V. N. Karinskii, Plasma Melting [in Russian], Metallurgiya, Moscow (1968).
9. M. F. Zhukov, A. S. Koroteev, and B. A. Uryukov, Applied Dynamics of a Thermal Plasma [in Russian], Nauka, Novosibirsk (1975).
10. B. S. Gavryushenko, R. Ya. Kucherov, A. V. Pustogarov, et al., "Study of the cathode and the adjacent region of the arc discharge in argon and in helium," Zh. Tekh. Fiz., 45, No. 10, 2119-2125 (1975).
11. É. M. Ésibyan and M. E. Danchenko, "Energy characteristics of an arc with a zirconium cathode," Avtomat. Svarka, No. 1, 5-8 (1970).

12. M. F. Zhukov, V. Ya. Smolyakov, and B. A. Uryukov, Electric-Arc Gas Heaters (Plasmatrons) [in Russian], Nauka, Moscow (1973).
13. S. P. Polyakov and M. G. Rozenberg, "Analysis and generalization of the current—voltage characteristics and the thermal characteristics of a 2-jet plasmatron," Inzh.-Fiz. Zh., 32, No. 6, 1043-1052 (1977).