GENERALIZATION OF THE CURRENT-VOLTAGE CHARACTERISTICS OF ONE-SIDED LINEAR ELECTRIC-ARC HEATERS STABILIZED WITH VARIOUS GASES

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The author presents criterial equations that can be used to generalize the current-voltage characteristics of a plasma generator in which the arc burns in a flow of air, nitrogen, argon, oxygen, helium, or hydrogen.

The arc voltage of a one-sided linear arc heater with vortex gas stabilization depends chiefly on the following factors: the geometric configuration of the discharge chamber, the pressure in the chamber, the nature of the stabilizing gas, its flow rate, and the strength of the current.

The effect of the geometry of the discharge chamber on the heater characteristics was examined in [1] and [2] for air and nitrogen, respectively. Moreover, in [1] the effect of pressure on the discharge parameters of a linear plasma generator was also investigated.

The present paper is a continuation of [1, 2] and is devoted to the effect of the nature of the gas on the plasma generator characteristics.

The experimental portion of this study was carried out using the heater described in [1, 2]. In the experiments we investigated sixteen typical discharge chamber configurations with identical and nonidentical electrode diameters. In the experiments with nonidentical electrode diameters the diameter of the open electrode was always less than that of the closed electrode. In all the experiments the polarity of the electrodes was the same: the open electrode was the anode, the closed electrode the cathode. As the working gases we used air, nitrogen, oxygen, hydrogen, helium, and argon. As the plasma generator power source we used mercury rectifiers with the following parameters: rated voltage 1650 V, rated current 1500 A.

We recorded the current-voltage characteristics for the following chamber configurations:

1) D = 3.5; d = 0.8 cm for argon, helium, and air;
2) D = 3.5; d = 1 cm for air;
3) D = 3.5; d = 1.4 cm for air and hydrogen;
4) D = 3.5; d = 1.8 cm for nitrogen;
5) D = 3.5; d = 2 cm for air;
6) D = 3.5; d = 2.7 cm for oxygen;
7) D = 2.6; d = 1.4; 1; 0.8 cm for air;
8) D = 2; d = 1.4; 1; 0.8 cm for air;
9) D = 1.4; d = 0.8 cm for argon, helium, and hydrogen;
10) D = d = 1 cm for all gases;
11) D = d = 2 cm for nitrogen and oxygen;
12) D = d = 4 cm for all gases.

The experiments showed that the effect of configuration and pressure on the arc voltage established in [1] for air obeys the same laws for the other gases (the pressure was measured at the end of the closed electrode).

Accordingly, we generalized the current-voltage characteristics individually for each gas by means of the criterial equation presented in [1]:

$$\frac{UD\sigma_0}{I} = f(\Pi_1;\ \Pi_2), \tag{1}$$

where

$$\Pi_1 = \frac{I^2}{GD\sigma_0 h_0}, \qquad \Pi_2 = \sqrt{\frac{\rho_0}{P_0}}\ \frac{PD^2}{G}.$$

Using a power-law approximation, we write

$$\frac{UD\sigma_0}{I} = A\left(\frac{I^2}{GD\sigma_0 h_0}\right)^{-b}\left(\sqrt{\frac{\rho_0}{P_0}}\ \frac{PD^2}{G}\right)^{c}. \tag{2}$$

Assuming that for a given gas the physical properties σ_0 and h_0 are constant, we rewrite Eq. (2) in the form

$$\frac{UD}{I} = A_1\left(\frac{I^2}{GD}\right)^{-b}\left(\frac{PD^2}{G}\right)^{c}. \tag{3}$$

The coefficients A_1, b, and c were calculated by the method of least squares both separately for the discharge chambers with nonidentical and identical anode and cathode diameters and together for all the chamber configurations tested for a given gas. The values of the coefficients and the maximum deviations of the experimental points from the approximate straight line are presented in the table.

The ranges of variation in the current and in the gasflow rate, within which the experimental data were generalized using (3), were as follows:

1) for air I = 30–1680 a, G = $0.63–40 \cdot 10^{-3}$ kg/sec;
2) for argon I = 50–1200 a, G = $1–30 \cdot 10^{-3}$ kg/sec;
3) for helium I = 13–560 a, G = $0.25–4 \cdot 10^{-3}$ kg/sec;
4) for hydrogen I = 80–920 a, G = $0.5–3 \cdot 10^{-3}$ kg/sec;
5) for nitrogen I = 100–1600 a, G = $2–40 \cdot 10^{-3}$ kg/sec;
6) for oxygen I = 220–1280 a, G = $4–30 \cdot 10^{-3}$ kg/sec.

The extent to which the generalization is satisfactory with respect to a specific gas can be seen from Fig. 1, which shows the generalized current-voltage characteristic for argon with (Fig. 1a) and without (Fig. 1b) allowance for the criterion $(\rho_0/P_0)^{1/2}PD^2/G$. In Fig. 1a along the ordinate axis we have plotted the complex N/Gh_0, the product of the nondetermining and determining criteria $UD\sigma_0/I$ and $I^2/GD\sigma_0h_0$, respectively. It is the ratio of the mean-mass enthalpy of the

Table

Coefficients and Exponents

Gas,	$D \neq d$				$D = d$				$D = d$ and $D \neq b$			
	b	c	A_1	Max. scatter, %	b	c	A_1	Max. scatter, %	b	c	A_1	Max. scatter, %
N_2	0.72	0.135	$1.76 \cdot 10^4$	±6	0.70	0.162	9850	±17	0.71	0.154	$1.23 \cdot 10^4$	±17
H_2	0.75	0.134	$1.15 \cdot 10^5$	±17	0.69	0.09	$4.63 \cdot 10^4$	±16	0.767	0.095	$2.27 \cdot 10^5$	±20
Air	0.653	0.21	1090	±20	0.692	0.26	2350	±16	0.66	0.23	1470	±29
O_2	0.59	0.077	1510	±5	0.617	0.156	1540	±5	0.58	0.249	292	±10
He	0.675	0.32	997	±13	0.675	0.402	420	±41	0.676	0.386	502	±41
Ar	0.587	0.234	138	±39	0.612	0.236	180.5	±14	0.602	0.238	172	±50

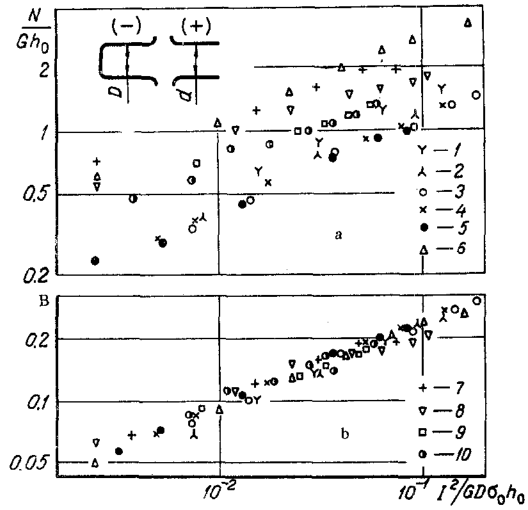

Fig. 1. Generalized current-voltage characteristic of a linear plasma generator with vortex stabilization without (a) and with (b) account for the criterion $(\rho_0/P_0)^{1/2}PD^2/G$ (gas—argon): 1–5) D = 0.01 m; d = 0.01 m; 6–10) D = 0.04 m; d = 0.04 m, gas flow rate: 1, 6) 1 kg/sec; 2, 7) 2; 3, 8) 4; 4, 9) 8; 5–10) $12 \cdot 10^{-3}$. $B = N/Gh_0/((\rho_0/P_0)^{1/2}PD^2/G)^{0.236}$.

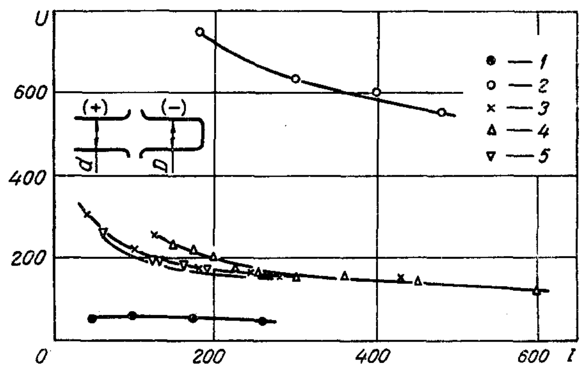

Fig. 2. Current-voltage characteristics of linear plasma generator with vortex gas stabilization (gas flow rate $2 \cdot 10^{-3}$ kg/sec; U, V; I, A; D = = d = $1 \cdot 10^{-2}$ m): 1) Ar; 2) H_2; 3) He; 4) N_2; 5) air.

heated gas without account for losses to the characteristic enthalpy. It is clear from Fig. 1 that the spread of the experimental points has been reduced by an order from ±130% to ±13%.

When various gases are blown over the arc at a constant mass flow rate and the same current a sharp difference in arc voltage is observed for the individual gases (Fig. 2). At the top is the characteristic for hydrogen, then follow the characteristics for air, nitrogen, and helium, and at the bottom the characteristic for argon.

The sharp difference between the characteristics is due to the considerable difference in the physical properties of the gases. The specific volumes of the gases differ very strongly, so that hydrogen flows over the arc at a much higher velocity than the other gases.

The electrical conductivities and enthalpies of the gases are also very different. For example, the initial specific enthalpies are 372, 59, 26.2, and 3 kJ/g for hydrogen, helium, oxygen, and argon, respectively (at $\sigma = 1\ \mathrm{ohm^{-1} \cdot cm^{-1}}$).

The data on thermal conductivity also indicate that hydrogen is a much better conductor of heat than the other gases.

In going over from the characteristics in dimensional form to the dimensionless criterial equations it is, first of all, necessary to find the characteristic values of the electrical conductivity σ_0 and enthalpy h_0. In [3] the relation $\sigma = f(h)$ was approximated by the power function $\sigma = \sigma_0(h/h_0)^n$. In this case as the characteristic values it is possible to take the properties at any of the points lying on the approximating curve. However, the relation $\sigma = f(h)$ has such a complicated form that it cannot be approximated by a single expression over a large range of variation of the enthalpy. The curve can be divided into three regions. In the first region $\sigma = 0$, since the gas is not ionized. In the second region, as h increases, thermal ionization begins accompanied by a rapid increase in conductivity. In the third region this increase slows down, since the increase in the number of electrons per unit volume is compensated by a decrease in the density of the gas. The last two regions can be approximated by power expressions with different exponents. The points of intersection of the straight lines approximating these regions are taken as the characteristic values.

In the region of small currents the current-voltage characteristics of the investigated discharge chambers fall steeply; then as the current increases the steepness diminishes. This indicates that the electrical conductivity starts by increasing, then the rate of increase gradually slows, i.e., the range of variation of the conductivity includes the second and third regions. Since in the experiments described the currents were generally measured in hundreds of amperes, we will consider the case of weak variation of the conductivity and introduce into the generalized formulas for taking into account the physical properties of the gas the angle of inclination of the third region in the approximating curve as an additional determining criterion.

With this criterion taken into account, Eq. (2) becomes

$$\frac{UD\sigma_0}{I} = A_2\left(\frac{I^2}{GD\sigma_0 h_0}\right)^{-b}\left(\sqrt{\frac{\rho_0}{P_0}}\frac{PD^2}{G}\right)n^{-k}. \quad (4)$$

The experiments on all the gases were correlated by the method of least squares. The calculated values of the coefficients follow:

$$A_2 = 0.45,\ b = 0.61,\ c = 0.245,\ k = 0.4.$$

As was to be expected, the accuracy of the generalizations over such a broad range of variation of the independent variables is still low (the rms error is 30%). This is due not only to the experimental errors but also to the discarding of certain unimportant criteria and the noncorrespondence between the approximating expressions and the actual laws.

Obviously, it is necessary to take into account other factors affecting the processes taking place in an electric arc.

Nonetheless, generalized formulas such as (4) may be useful in designing various forms of electric-arc equipment, since they make it possible to reduce considerably the scope of the preliminary investigations.

NOTATION

U is the voltage, V; I is the current, A; N is the power, kW; D is the diameter of the closed electrode, m; d is the diameter of the outlet electrode, m; G is the gas flow rate, kg/sec; P is the pressure in the chamber, N/m^2; σ_0 is the characteristic value of the electrical conductivity, 1/ohm · m; h_0 is the characteristic value of the enthalpy, kJ/g; ρ_0 is the characteristic value of the density, kg/m^3; A, A_1, and A_2 are proportionality factors; b, c, k, and n are exponents.

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