CURRENT-VOLTAGE CHARACTERISTICS AND EMF OF AN ELECTRIC-ARC HEATER OPERATING WITH VARIOUS GASES

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The stationary and dynamic current-voltage characteristics of an electric-arc heater with an argon, nitrogen, air, and oxygen stabilized arc are determined. An empirical expression for calculating the current-voltage characteristics for various working gases is proposed.

The ever growing application of electric-arc heaters in various branches of science and technology poses continuously growing requirements in regard to operational procedures and service life. For example, the use of plasmatrons for simulating the conditions encountered by a vehicle that passes through dense atmospheric layers of various planets involves electric-arc heating of inert and aggressive gases over a wide range of temperatures and pressures.

Specific design features of a heater and some characteristics of the generated jet are examined in [1, 2].

STATIONARY CURRENT-VOLTAGE CHARACTERISTICS

During the past few years, much attention has been given to the determination of the mechanism of arc burning in gas vortex-stabilized plasmatrons. When a portion of the electric arc is aligned with the axis of a hollow cylindrical electrode—as is the case in the plasmatron under study—arc burning is accompanied by a complex motion of the base spot across the inner electrode surface. This phenomenon is due to continuous arc shunting to the electrode wall [3, 4]. For a mean mass velocity of 850 to 900 m/sec of the gas through a cylindrical electrode, the mean axial velocity component of the cathode spot in the output electrode is on the order of 180 m/sec. Here, the electric-arc parameters are subjected to continuous changes. Under certain conditions, the voltage fluctuations may reach 40 to 50% of their mean value [3, 4].

Such an arc-burning mechanism indicates that, normally, the mean values of the current and voltage should be used in deriving the stationary current-voltage characteristics.

The burning of a plasmatron arc is influenced by a number of factors. Hence, the current-voltage characteristics depend on the flow rate of the working gas, the type of gas, the gas pressure and type of gas supply, as well as on the geometrical dimensions, shape, and arrangement of the electrodes, the material and polarity of the electrodes, the magnitude of the proper and external magnetic field, and other factors.

For plasmatrons with a self-adjusting arc length (the geometry and spacing of the electrodes have no significant effect on $U = f(I)$), all other conditions being equal, it may be assumed that the current-voltage characteristic is essentially determined by the physical properties of the gas referred to a certain characteristic temperature and by the flow rate of the gas.

The stationary current-voltage characteristics of a gas vortex-stabilized electric-arc heater were measured for the case where the output electrode serves as the anode. The arc current was determined by means of a wire-wound rheostat with a resistance ranging from 0.2 to 0.6 ohms, and was calculated from the voltage drop at 75 ShS type shunting devices (750 A, 75 mV), which was recorded within an accuracy of ±2.5% with a nine-loop SO-Simens oscillograph. The voltage was read directly at the electrodes between which the electric arc was burning and was recorded, within an accuracy of ±1.5%, with an oscillograph.

Figure 1 shows the stationary current-voltage characteristics for operation with nitrogen. As usual, the characteristics tend toward the high voltage-drop values with increasing gas flow rate.

The spread of the experimental points (Fig. 1) is typical for a plasmatron of this design [1, 8].

The family of stationary current-voltage characteristics determines the operating range of the parameters of a plasmatron of this type in the aerodynamic rotation of the base points of the arc. At currents above 1000 to 1200 A, the electrodes become unserviceable due to the onset of intense erosion. At currents smaller than a certain value $I_{\min}$ [5, 6], the arc becomes unstable and extinguishes.

Figures 2 and 3 show the current-voltage characteristics shift toward the higher voltage-drop values when the flow rate of air and oxygen is increased.

An arc burning in argon (Fig. 3b) exhibits a peculiar behavior. The voltage drop at the arc is roughly 3 to 3.5 times less than for operation with oxygen and other gases. The stationary characteristic $U = f(I)$ of an argon arc in the plasmatron under study is horizontal ($U = \text{const}$). The spread of experimental points observed in this case (up to 25%) is an indication for unstable burning of the arc under these conditions.

DYNAMIC CURRENT-VOLTAGE CHARACTERISTICS

Of great interest for the operation of the plasmatron are its dynamic current-voltage characteristics; i.e., the characteristics measured when the current varies at a rate at which steady-state equilibrium cannot be established [5].

The dynamic current-voltage characteristics were measured with an H-359 two-coordinate ammeter, which made it possible to record the current as a function of the voltage.

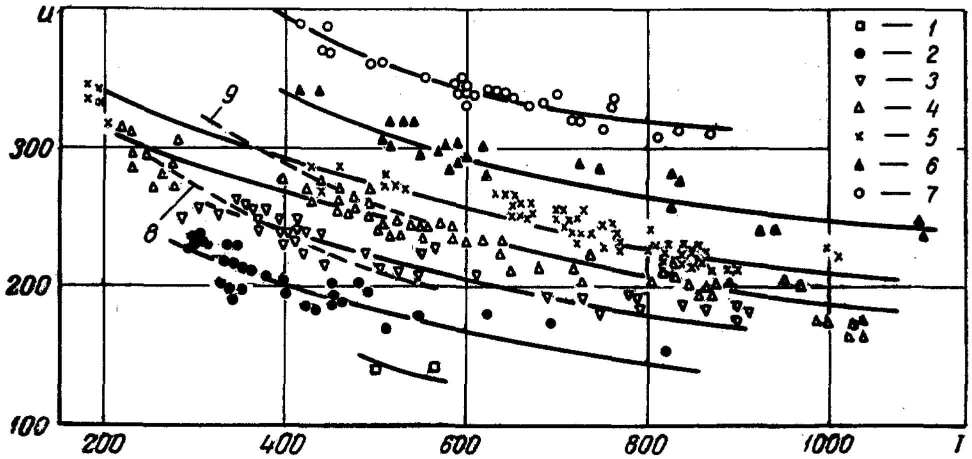

Fig. 1. Current-voltage characteristics of a plasmatron employing nitrogen as the working gas (d_{an} = 15 mm; d_{cath} = 20 mm). Stationary: 1) G_{N_2} = 2 g/sec; 2) 3 g/sec; 3) 4 g/sec; 4) 5 g/sec; 5) 6 g/sec; 6) 7.0–7.5 g/sec; 7) 10 g/sec. Dynamic: 8) 6 g/sec; 9) 8 g/sec.

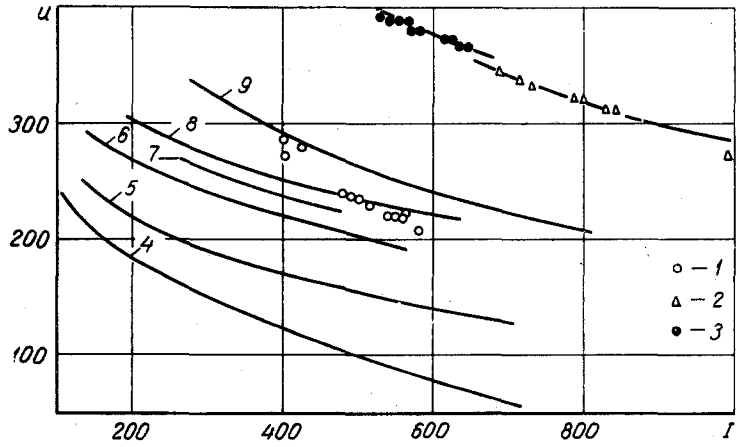

Fig. 2. Current-voltage characteristics of a plasmatron employing air as the working gas (d_{an} = 15 mm; d_{cath} = 20 mm). Stationary: 1) G_{air} = 5.9 g/sec; 2) 11.5 g/sec; 3) 13.25 g/sec. Dynamic: 4) 3.4 g/sec; 5) 4 g/sec; 6) 6.5 g/sec; 7) 6.85 g/sec; 8) 8 g/sec; 9) 10 g/sec.

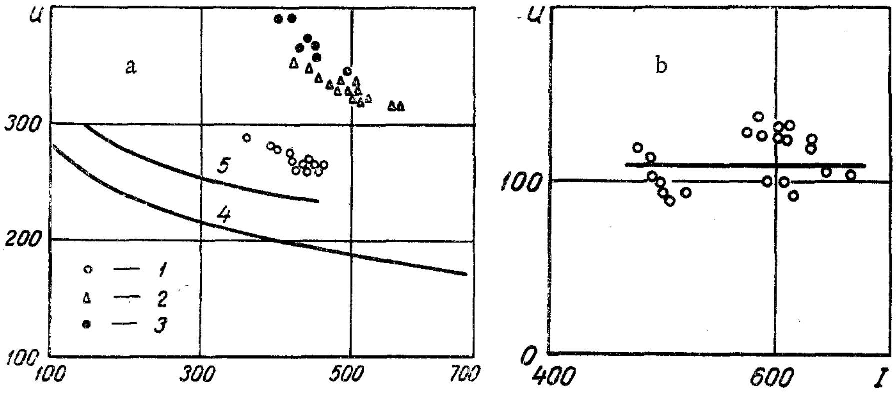

Fig. 3. Current-voltage characteristics of a plasmatron operating with oxygen (a) and argon (b) (d_{an} = 15 mm; d_{cath} = 20 mm). a) Stationary: 1) G_{O_2} = 8.5 g/sec; 2) 12.2 g/sec; 3) 13.8 g/sec. Dynamic: 4) 6 g/sec; 5) 8 g/sec. b) Stationary: G_{Ar} = 14.35 g/sec.

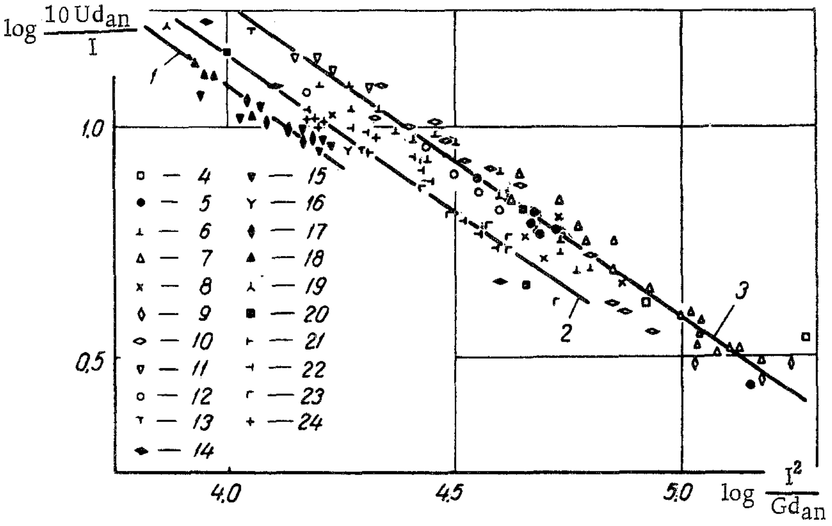

Fig. 4. Generalized current-voltage characteristics of a plasmatron operating with various gases. Curve 1, oxygen: 14) G_{O_2} = 4.0 g/sec [8]; 15) 8.5 g/sec; 16) 11.5 g/sec; 17) 12.25 g/sec; 18) 13.8 g/sec; 19) 4 g/sec [3]. Curve 2, air: 20) 1.01 g/sec [6]; 21) 2.05 g/sec [6]; 22) 5.9 g/sec; 23) 11.5 g/sec; 24) 13.25 g/sec. Curve 3, nitrogen; 4) 2 g/sec; 5) 3 g/sec; 6) 4 g/sec; 7) 5 g/sec; 8) 6 g/sec; 9) 7 g/sec; 10) 8 g/sec; 11) 9 g/sec; 12) 10 g/sec; 13) 4 g/sec [8].

For checking purposes, the current and the voltage were simultaneously recorded with an oscillograph. An aqueous rheostat (a tank filled with an Na_2CO_3 solution and containing mobile and fixed plates) was used in the experiments in addition to the wire-wound rheostat. The aqueous rheostat and the wire-wound device were series connected in the circuit. The rate of arc-current variation (dI/dt) could be controlled over a range from 10 to 60 A/sec by varying the rate of immersion of the mobile rheostat plates into the solution.

The dynamic current-voltage characteristics of the plasmatron measured for operation with nitrogen, air, and oxygen (Figs. 1–3) lie somewhat lower than the stationary characteristics. Thus, for $G = 6$ g/sec, the dynamic characteristics differ from the stationary ones by 22% in the case of nitrogen, and by 19% in the case of air. This difference is somewhat less when the arc is blown by oxygen.

This should be attributed to the kinetics of the elementary processes in the arc and at its base spots, and reflects the rise time of processes which occur in the arc and which affect directly the shape of the current-voltage characteristics. The influence of the factors responsible for the thermal time constant is that the electrical conductivity (resistance) of the gas is determined at any moment of time not only by the processes that take place at this moment but also by the preceding ones. In other words, the current rise time is directly associated with (1) the final rate of variation of the enthalpy of the arc ($c_p = dH/d\tau$), and (2) the final rate of charge-carrier accumulation and dissipation in the gas [7]. The phenomena are due to ionization and deionization of the working gas. If the ionization and deionization rates of the gas are comparable to the rate at which the voltage (current) drop varies at the arc, then the dynamic characteristics can differ appreciably from the stationary characteristics.

In the given case, the measurement of the dynamic current-voltage characteristics was accompanied by a current drop. This may possibly affect the dynamic characteristics, since the charge-carrier concentration in the arc increases somewhat above its value for the preceding moments of time, the arc resistance decreases and, consequently, the voltage drop at the arc is somewhat smaller.

GENERALIZED CURRENT-VOLTAGE CHARACTERISTICS

Recently, much attention has been given to the generalization of current-voltage characteristics [3, 8–10]. According to the theory of dimensionless generalization of empirical plasmatron relations, the generalized characteristics can be extended to the unexplored regions of electric-arc heater operation. A number of different criteria have been obtained in dimensional and dimensionless form which characterize the relations between the principal geometrical dimensions, the thermal factors, and the dimensionless numbers which describe the properties of the working gas as a function of the parameters of the medium.

The experimental data concerning the current-voltage characteristics obtained for the working gases under study were processed in dimensionless form (Fig. 4). The figure shows the influence of the gas properties on the arc characteristics, evident in the fact that the experimental points lie on straight lines that are characteristic of each gas. It may be seen that the straight lines located highest in Fig. 4 correspond to the working gases with the smallest molecular weight (nitrogen, 28.02; air, 28.97; and oxygen, 32.00).

Certain, purely qualitative considerations indicate that the nature of arc burning (the current-voltage characteristic of the arc) must be appreciably affected by the heat transfer processes in the discharge chamber that depend on the physical properties of the gas. Such properties are first of all the heat capacity c_p and the thermal conductivity λ.

According to molecular kinetic theory of ideal gases, these properties at constant pressures and temperatures are functions of a single physical quantity, the molecular weight M. Hence, in order to determine the influence of the physical properties of the gas on the current-voltage characteristics, it is necessary to introduce a correction factor which depends on molecular weight.

Since the experimental points of the gases studied lie distinctly along parallel straight lines plotted in $\log((T^2)/Gd)$; $\log((10\,Ud)/I)$ coordinates, the equation of such a straight line can be written in general form as follows:

$$\log\frac{10Ud}{I} + a\log\frac{I^2}{Gd} - b = 0. \tag{1}$$

The equation includes the coefficients a and b. For the gases under study, the coefficient a may be taken as a constant with an error of less than 1%. It can be seen from Fig. 4 that the coefficient b, defined by the coordinate of the point of intersection of the straight line with the y axis, depends on the type of gas. It was, therefore, expressed through the molecular weight of the gas. A curve showing the dependence of coefficient b on the molecular weight was plotted for this purpose. It was found that for $28 < M < 32$, this curve can be approximated by a straight line.

By substituting this relation into Eq. (1) solved with respect to U, one arrives at

$$U = \frac{5620}{10^{0.03M}}\left(\frac{G^2}{Id}\right)^{1/3}. \tag{2}$$

This equation approximates the experimental curves with an error of roughly 14%. In order to improve the approximation accuracy, a correction factor $\left(\frac{d}{G}\right)^{0.05}$ is introduced in accordance with [3], getting

$$U = \frac{5620}{10^{0.03M}}\left(\frac{G^2}{Id}\right)^{1/3}\left(\frac{d}{G}\right)^{0.05}. \tag{3}$$

This formula makes it possible to calculate, within the experimental accuracy (7%), the current-voltage characteristics of a gas vortex-stabilized electric-arc heater for the gases under study.

In conclusion, it should be noted that the experimental data obtained for argon, which are not shown in Fig. 4, do not conform with the general rule. They lie appreciably lower [$\log(10Ud)/I = 0.4$–0.6 and $\log(I^2/Gd) = 3.9$–4.25] and exhibit a large scatter.

HEATER EFFICIENCY

Substantial thermal losses to the cooled elements (electrodes, damping chamber) and energy dissipation at the ballast resistance are characteristic of electric-arc devices. To assess the energy losses at the ballast resistance, we introduce the electric efficiency of the device in the form of the ratio of the power emanated from the arc to the supply power:

$$\eta_{\text{el}} = \frac{N_{\text{arc}}}{N_{\text{source}}} = \frac{U_{\text{arc}}}{U_{\text{source}}} = \frac{R_{\text{arc}}}{R_{б} + R_{\text{arc}}}. \qquad (4)$$

Since $U_{\text{source}} = U_{\text{arc}} + U_b$ (where U_b is the voltage drop at the ballast resistance), the electric efficiency of the device will depend on the power redistribution at the arc and at the instrument multiplier. Figure 5a shows the electric efficiency as a function of the gas flow rate for plasmatron operation with argon, nitrogen, air, and oxygen. It can be seen that for the plasmatron under study, η_{el} depends strongly on the type of the working gas employed. The highest efficiency is to be observed for operation with nitrogen, which has the smallest molecular weight of the gases studied. The lowest efficiency is observed for argon (largest molecular weight); it is slightly above 0.2 at a flow rate of G = 14.35 g/sec. The quantity η_{el} increases with the flow rate of the working gas, its relative increase diminishing with increasing flow rate. Hence, for prolonged operation of an electric-arc device with various gases, when economy of operation becomes an important factor, it is advisable to select an optimum mode that corresponds to $\eta_{\text{el}}^{\max}$.

In order to assess the thermal losses in the combustion chamber, we introduce the thermal efficiency of the device, in the form of the ratio of the power absorbed by the working gas to the power emanated from the arc:

$$\eta_t = \frac{N_{\text{total}}}{N_{\text{arc}}} = 1 - \frac{N_{\text{loss}}}{N_{\text{arc}}}, \qquad (5)$$

where $N_{\text{total}} = N_{\text{arc}} - N_{\text{loss}}$ is the power consumed for heating the working gas.

The power released to the cooled elements (N_{loss}) is determined from measurements of the flow rate and heating of the cooling water.

The value of η_t depends on the design and geometrical dimensions of the plasmatron, the electrode material, the flow rate, pressure, and type of the working gas, the electrical parameters of the arc, and so forth.

Inasmuch as the thermal losses to the electrodes depend strongly on the current, the influence of the current on the thermal efficiency of the plasmatron was studied. Figure 5b shows the results of the investigation for operation with nitrogen, air, and oxygen. It can be seen that at small values of the current, η_t is almost independent of I. A further increase in current strength leads to a decrease in thermal efficiency. The thermal efficiency is slightly higher for operation with nitrogen than with air and oxygen. For an argon-stabilized arc (G = 14.35 g/sec and I = 500 to 600 A), the efficiency variations ranged from 0.25 to 0.42.

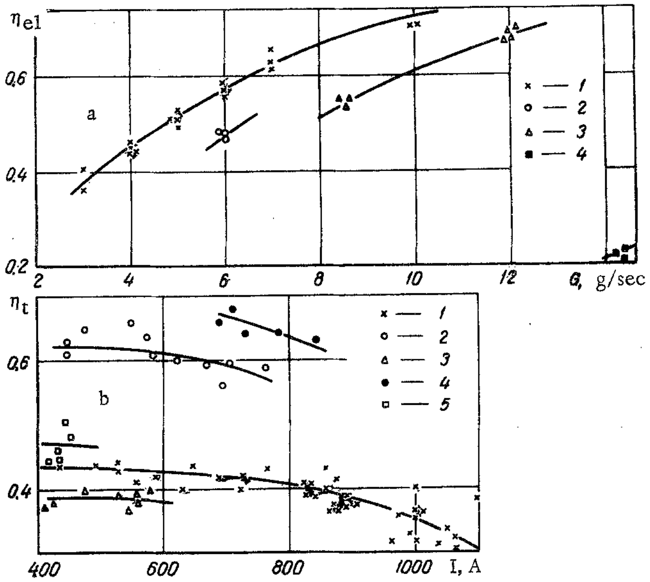

Fig. 5. a) Electric efficiency as a function of the gas flow rate for the operation with various gases (1, nitrogen; 2, air; 3, oxygen; 4, argon; I = 500 A) and b) thermal efficiency as a function of current intensity (nitrogen: 1) G = 6.0 g/sec; 2) 10.0 g/sec; air: 3) 5.9 g/sec; 4) 11.5 g/sec; oxygen: 5) 8.5 g/sec). $d_{\text{an}} = 15$ mm; $d_{\text{cath}} = 20$ mm.

NOTATION

U_{source} is the supply voltage; R_{arc} is the arc resistance; R_b is the resistance of the ballast rheostat.

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