AN EXPERIMENTAL STUDY CONCERNING THE ELECTRICAL AND THE THERMAL CHARACTERISTICS OF STABILIZED ARCS

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Results are shown of an experimental study concerning the electric field intensity and the useful power of a plasma jet as well as the electron and the atom–ion gas temperature in an argon arc under atmospheric pressure.

A great deal of experimental data concerning the volt–ampere characteristics of plasma jets has been accumulated by now, making it possible to arrive at some generalization in criterial form [1-4]. The prevailing opinion that these universal volt–ampere characteristics of plasmatron arcs are applicable to the development of new designs and of high-power devices is not always correct, because these characteristics describe an arc only as a load element without accounting for the useful power and the efficiency of a plasmatron as functions of various parameters [5-7].

The authors have made an integrated study concerning both the electrical and the thermal characteristics of plasmatrons as functions of the arc length, the chamber diameter, the arc current, and the flow rate of the plasma-generating gas (argon). The experiments were performed on a test stand whose thorough description can be found in [8]. We used a plasmatron with a pin cathode shaped into a cone and a segmented anode. The inside diameter of a segment was 0.6 to 1.2 cm, the flow rate of argon ranged from 0.25 to 2.0 g/sec and the arc length l_a was varied through the electric circuit from the self-sustaining value to $l_a \simeq 16$ cm, while glow occurred along the plasmatron channel between the cathode and one of the anode segments.

For all operating modes we determined the volt–ampere characteristics (some of them have been analyzed in [8, 9]) and the longitudinal distribution of potential, the latter by measuring the voltage from successive channel segments to cathode. A thorough description of the measurement procedure can be found in [8]. By differentiating these distribution curves, we found the longitudinal component of the electric field intensity in the arc column as a function of its length (Fig. 1). The electric field intensity was also determined from the volt–ampere characteristics, on the basis of the voltage increment following a change in the arc length. The electric field intensity data obtained by both methods are in close agreement.

The useful power of a plasma jet and the heat dissipated in all its components were determined by calorimeter measurements of the cooling water. The measuring procedure has been described and the data have been evaluated very thoroughly in [8].

As has been mentioned earlier, the volt–ampere characteristic is an integral one and cannot provide a precise enough explanation of the processes which occur in an arc. A more precise explanation can be obtained from the distribution of electric field intensity along the arc. It has been shown already in [8] that the distribution of potential along the arc does not depend on the arc length and, therefore, a variation of the electric field intensity along the arc (Fig. 1) is the same for arcs of different lengths (l_a is measured beginning at the cathode).

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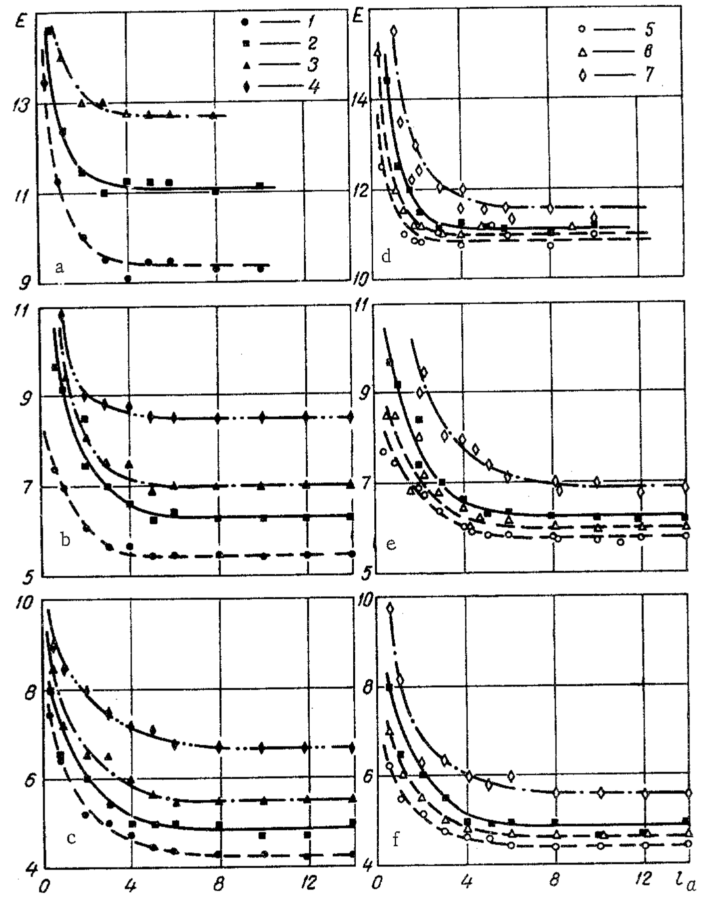

Fig. 1. Electric field intensity E (V/cm) in the arc column as a function of the arc length l_a (cm). a, b, c) At an argon flow rate G = 0.67 g/sec; 1) current I = 100 A; 2) 150 A; 3) 200 A; 4) 300 A: d, e, f) at a current I = 150 A; 5) argon flow rate G = 0.25 g/sec; 6) 0.39 g/sec; 7) 1.23 g/sec. Diameter of the arc channel d = 0.6 cm (a, d), 1.0 cm (b, e), 1.2 cm (c, f).

The electric field intensity decreases along the arc down to a definite threshold, characterizing a transition of the arc to a segment with cylindrical symmetry, where the plasma parameters along the arc remain constant. In this region the electric field intensity depends only weakly on the flow rate of the plasma-generating gas but strongly on the arc current and on the channel diameter, which agrees closely with the data in [10, 11]. In the initial arc region, where the plasma parameters vary and where also a gas stream appears, one notes a considerable change in E as a function of l_a. This is so, because the quantity of gas entering the arc in the initial region depends on the static-pressure gradient due to the current flow. At low gas flow rates, lower than the rate of gas which could "overcome" the static-pressure gradient, all the plasma-generating gas is sucked in by the arc. At high gas flow rates, the excess gas, i. e., the portion not trapped in the initial region, blows on the arc compressing and stabilizing it.

The combined effect of arc current and gas flow rate on the electric field intensity is illustrated in Fig. 2. At low currents, 50-100 A, the arc is partly vented by the gas and, therefore, a change in the gas flow rate has a strong effect on the distribution of electric field intensity along the arc, since at a constant current there blows through the arc a definite (almost constant) fraction of the gas while the remainder, which increases with the flow rate, blows around the arc. At high currents, about 300 A, and at gas flow rates from 0.25 to 1.23 g/sec the distribution of electric field intensity along the arc is essentially determined by the arc current and by the interaction between arc and channel wall alone, because all the gas then, regardless of its flow rate, is sucked into the initial region and no gas blows on the arc.

The thermal characteristics, including the arc temperature and the useful heat in the outflowing plasma jet depend not only on the channel diameter, on the gas flow rate, and on the arc current, but also on the arc length. The effect of the arc length on the thermal characteristics at various arc currents in a channel with a fixed diameter and at a fixed gas flow rate has been analyzed in [8], where it also has been established that the useful power of the outflowing plasma jet reaches a maximum at some arc length. The decrease in useful power with an increase in the arc length beyond that optimum has to do with arc oscillations relative to the axis of the plasmatron channel. A similar pattern is noted in plasmatrons with various diameters of the arc channel [12]. This mechanism of power dissipation in a plasma jet has been confirmed by turbulence measurements [13] showing that fluctuations of the velocity head increase in the plasma jet where the useful power decreases.

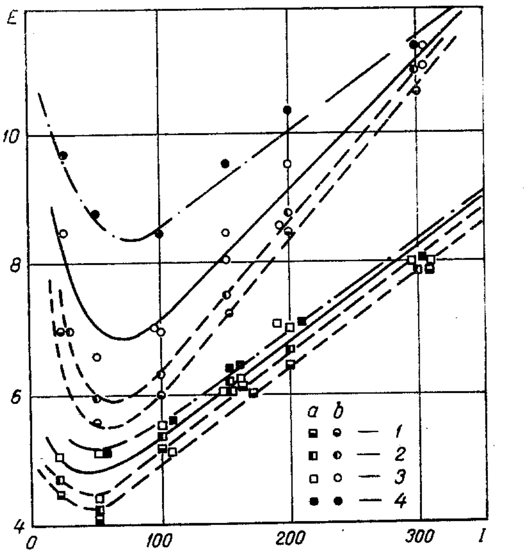

Fig. 2. Electric field intensity E (V/cm) in the arc column as a function of the arc current I (A); 1) at a gas flow rate G = 0.25 g/sec; 2) 0.39 g/sec; 3) 0.67 g/sec; 4) 1.23 g/sec, and at an arc length $l_a = 11$ cm (a), 2.2 cm (b). Channel diameter 1.0 cm.

The shifting of the power maximum with varying arc length depends largely on the gas flow rate and on the diameter of the arc channel, but is not much affected by the arc current. Thus, at an argon flow rate of 0.25 g/sec in a plasmatron with a channel 1.0 cm in diameter the plasma jet attains its maximum power when the arc length is 6-8 cm, while at an argon flow rate of 1.23 g/sec the maximum occurs when the arc is 12-16 cm long. As the diameter of the plasmatron channel decreases, the maximum useful power shifts toward shorter arcs. These relations between the useful power of a plasma jet and the arc length are well described by the expression

$$\frac{Hd_0}{I} = f\left(\mathrm{Re}, \frac{l_a}{d}, \frac{d_0}{d}\right), \tag{1}$$

which, letting $d_0 = 1$, can be transformed into

$$\frac{H}{I} = \varphi\left(Gd, \frac{l_a}{d}\right). \tag{2}$$

Relation (2) has been plotted in Fig. 3, where test data are shown for various channel diameters and for various gas flow rates at an arc current from 50 to 300 A.

According to Fig. 3, the maximum value of the enthalpy factor H/I or of P_{use}/GI is 32 J/g · A within ±40% accuracy and with the dimensionless number $(Gd)^{-0.5} l_a/d = 12$.

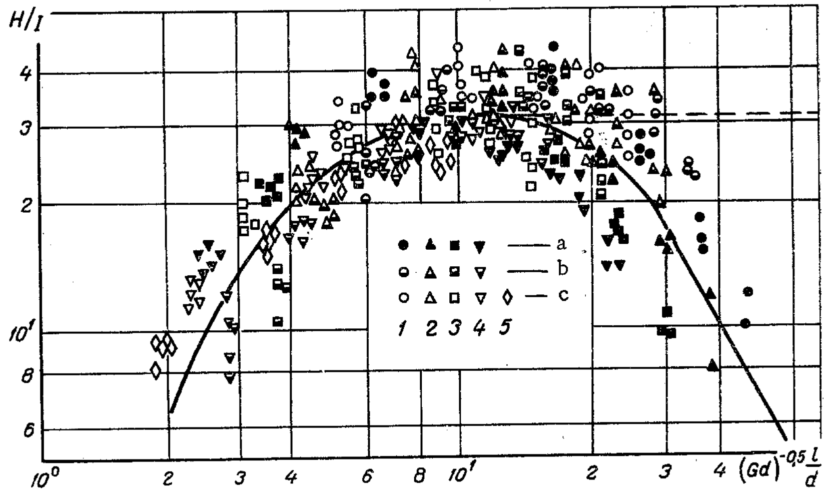

Fig. 3. Enthalpy factor H/I (J/g · A) as a function of the dimensionless number $(Gd)^{-0.5} l_a/d$, for channel diameters a) d = 0.6 cm; b) 1.0 cm; c) 1.2 cm, and for argon flow rates 1) G = 0.25 g/sec; 2) 0.39 g/sec; 3) 0.67 g/sec; 4) 1.23 g/sec; 5) 2.0 g/sec. (Dashed line: along arc. Solid line: versus arc length.)

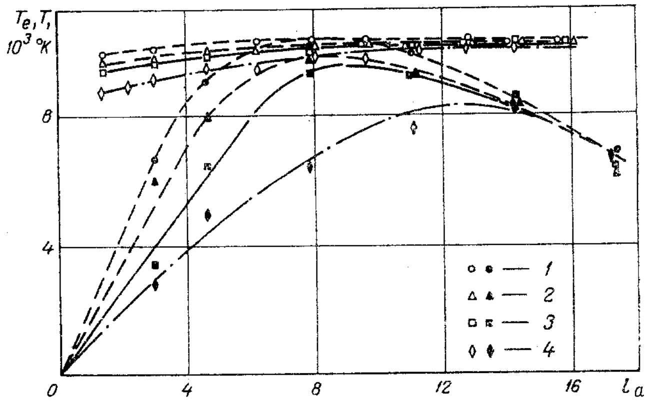

Fig. 4. Electron temperature T_e (°K; light dots) and atom–ion gas temperature T (°K; dark dots) as functions of the arc length l_a (cm) at a current I = 150 A and at argon flow rates 1) G = 0.25 g/sec; 2) 0.39 g /sec; 3) 0.67 g/sec; 4) 1.23 g/sec, in a channel 1.0 cm in diameter.

Consequently, the maximum useful power of a plasma jet is determined as follows:

$$P_{\text{use}} = 32GI \text{ (W)} \tag{3}$$

at an optimum arc length

$$l_a = 12d\sqrt{Gd}. \tag{4}$$

These formulas are important for the design of plasmatrons.

A comparison between the useful power of a plasma jet and the electric field intensity, both as functions of the arc length at various currents as well as various gas flow rates and various channel diameters, has shown that the maximum useful power occurs in the arc region where the electric field intensity begins to become independent of the arc length, i. e., in the region of transition to a segment with cylindrical symmetry. As the arc length increases, therefore, the useful power increases until an initial arc segment is completely formed in which the longitudinal static-pressure gradient, apparently, prevents arc instability and oscillations. Otherwise, increasing the arc length will lead to arc oscillations with resulting higher heat losses at the walls along the entire plasmatron channel, which will reduce the useful power of the plasma jet (solid line in Fig. 3). On the same diagram is shown, for comparison, a dashed line which represents the heating of the gas over the length of a stable arc.

The difference between the electric field intensity versus arc length and the useful power versus arc length characteristics has to do with the nonequilibrium of the argon plasma [14] due to a weak relation between the atom–ion temperature and the electron temperature.

The effect of the gas flow rate on the thermal nonequilibrium of the plasma is illustrated in Fig. 4. The difference between temperatures T_e and T is largely determined by the arc length: in short arcs nonequilibrium occurs because of the insufficient time for the gas to heat up along the arc, while in long arcs nonequilibrium occurs because of arc oscillations with resulting heat losses in the channel walls. We are considering here mean-over-the-section electron and gas temperatures, so that some slight nonequilibrium may be attributed to a temperature difference within the peripheral region of the arc. In the initial arc region, however, where the mean electron temperature is much higher than the gas temperature, nonequilibrium occurs evidently also within the axial region of the arc.

NOTATION

l_a is the length of arc;
E is the electric field intensity in the arc column;
d is the diameter of arc channel;
d_0 is the unit diameter;
H is the enthalpy;
I_a is the arc current;

Re is the Reynolds number;

T_e is the electron temperature;

T is the atom – ion gas temperature.

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