THERMAL REGIME OF AN ELECTRIC ARC

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The burning stability of an arc in a stream of gas is estimated on the basis of the energy balance. It is shown that instability and the presence of a drooping branch on the current-voltage characteristic may be attributed to nonlinearity of the conductivity of a weakly ionized plasma. Critical values of the voltage for arc quenching and striking are indicated.

In connection with the development of certain branches of technology (plasma generators, etc.) there has been a growth of interest in problems relating to the physics of electric arcs. Special attention has been paid to the burning of an arc in a transverse gas flow. It is known that intense blowing leads to quenching of the arc discharge. This effect is widely used in various arc-arresting devices [1]. The interaction of an arc with a gas flow is also important in connection with the operation of plasma generators in which the stream of gas absorbs the thermal energy of the arc. A study of the operation of dc plasma generators [2] has shown that an arc segment burning at right angles to a gas flow moves in the direction of the flow together with the gas. However, if the electrodes are of finite length, on reaching the edge the middle of the discharge continues to move, causing the arc to deflect (from a loop). The deflection increases with increase in velocity. Starting from a certain value of the deflection, the discharge in the middle of the arc is periodically quenched and simultaneously restored by shunting along chords, after which it again advances toward the end of the arc, and so on. Similar behavior was observed in [3] with increase in pressure. In [2] the following explanation is offered: as the arc is drawn out, its length increases leading to an increase in voltage in the burning zone. Accordingly, breakdown along chords becomes possible. In [3] it was shown that drifting of the arc column is associated with the interaction of arc ions and neutral atoms of the gas stream. This interaction is stronger when the drift velocity of the ions in the electric field is lower. Hence the relationship between the deflection and pressure observed in [3].

The basic effect associated with a blown arc is the removal of energy, cooling the column. A direct consequence of this is a reduction in conductivity. In view of the sharp dependence of conductivity on temperature, this, in turn, may lead to quenching of the arc.

It is natural to suppose that in this case there will be a certain minimum voltage below which the arc is quenched.

The arc voltage [6] is composed of the voltage drop in the electrode region and in the arc column itself. The voltage drop close to the electrodes depends substantially on the current-closing mechanism. In the general case this mechanism depends on many factors (electrode material, current intensity, etc.), whose role is not adequately understood. We will therefore confine outselves to a consideration of the process of energy transfer in the middle of the arc column, neglecting in particular, the removal of heat through the electrodes. Changes in the shape of the arc column due to the gas flow will also be disregarded.

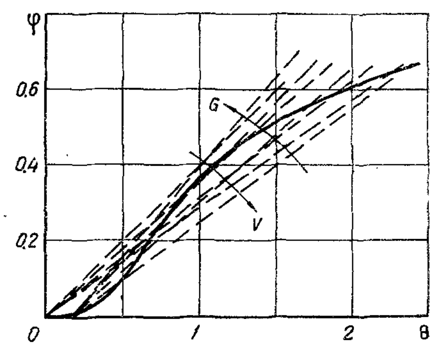

Fig. 1. Graphical solution of Eq. (6): broken line for $\varphi_1 = A(\Theta - \Theta_0)$; continuous line for $\varphi_2 = \exp(-1/\Theta)$.

To obtain an approximate solution of this extremely schematized problem we will employ the so-called "zero-dimensional" scheme widely used in the theory of the thermal regime of combustion [4]. We write the basic equation for the power balance in the arc

$$Q_1 = Q_2. \tag{1}$$

The first of these quantities Q_1 is composed of the heat content absorbed by the gas flow in the arc and the heat released by the surrounding medium

$$Q_1 = (Gc_p + \alpha S)(T - T_0). \tag{2}$$

In solving the problem we will assume that the plasma is in temperature equilibrium, i.e., that the temperatures of the electronic, ionic, and neutral components are the same: $T_e = T_i = T$. In fact, since the energy is supplied to the electron gas, but removed mainly from the neutrals, in certain gases in the stationary state temperature disequilibrium may be maintained if the blowing is intense. In [3] this effect was used in connection with an argon-cesium mixture to obtain a nonequilibrium plasma.

Since in technical equipment the arc usually burns under constant voltage conditions (ensured by inserting a ballast resistance), we will write the output power, as usual, in the form

$$Q_2 = IV = V^2/R. \tag{3}$$

Substituting expressions (2) and (3) in Eq. (1), we obtain

$$(Gc_p + \alpha S)(T - T_0) = V^2/R. \tag{4}$$

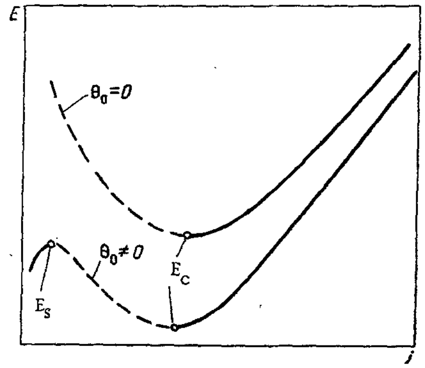

Fig. 2. Current-voltage characteristic of segment of arc discharge (continuous line—stable, broken line—unstable).

We also take the following expression for the temperature dependence of the electrical conductivity:

$$\sigma = \sigma_0 \exp(-eV_i/kT). \qquad (5)$$

Then Eq. (4) can be written, using the notation $\Theta = T/T_i = kT/eV_i$, in the dimensionless form

$$A(\Theta - \Theta_0) = \exp(-1/\Theta), \qquad (6)$$

where A is a dimensionless function depending on the arc geometry, the heat transfer coefficient, the gas flow rate, and the applied voltage:

$$A = \frac{l}{\sigma_0 S_0 V^2}(Gc_p + \alpha S).$$

In particular, an increase in the parameter A corresponds to an increase in gas flow rate or heat transfer and a fall in voltage. The symbol Θ_0 denotes the dimensionless ambient temperature. In discussing the results we will have chiefly in mind the dependence of A on the external factors, gas flow rate G and applied voltage V, since the laws of heat transfer for an arc in a gas flow have received very little attention. We note merely that an estimate of the heat transfer due to radiation and conduction from the arc column shows that, as a rule, they are less than the conductive heat transfer by an order of magnitude.

Stationary burning of an arc in a gas flow should correspond to the conditions defined by the solution of transcendental equation (6). Its solution is best obtained graphically, from the intersection of the family of straight lines with the exponential curve (Fig. 1). The directions of increase in voltage and gas flow rate are indicated on the figure by arrows.

It is clear from the figure that when $\Theta_0 \ll \Theta$ (for simplicity $\Theta_0 \approx 0$) there are two stationary solutions. One of these (the lesser) is thermally unstable. This means that any temperature fluctuation at that point leads to a deviation that increases until an upper stable value is reached. It is also clear from the figure that there is a critical point (where the straight line touches the exponential curve) at which the arc collapses.

Using as parameter the value of A, which, other things being equal, is inversely proportional to the square of the applied voltage, we can construct the relation between the voltage and the current density in the discharge (current-voltage characteristic).

In Fig. 2 these characteristics are presented schematically for the limiting case $\Theta_0 \approx 0$ and the general case $\Theta_0 \neq 0$. When $\Theta_0 = 0$, the current-voltage characteristics of the plasma column have two segments, a drooping and an ascending branch. All the points on the drooping branch of the characteristic ($\partial E/\partial j < 0$) correspond to unstable states of the discharge obtained from the solution of Eq. (7).

Figure 2 also shows that at a given gas flow rate there is a minimum value of the potential difference on the arc segment at which the arc can burn. Since we are concerned with phenomena that take place in the body of the arc column, it makes sense (particularly in dimensionless form) to use the quantities j and E instead of I and V. In the general case when $\Theta_0 \neq 0$, as may be seen from the same figure, the nonuniqueness of the current-voltage characteristic increases: three stationary values of the current density j correspond to the same value of E. Correspondingly, the characteristic consists of one (central) drooping and two ascending (stable) branches. The first of these lies in the region of very small currents and is conditioned by the semi-self-maintained conductivity of the heated gas; the second lies in the region of currents where the arc channel is close to complete ionization. In this case there are also two critical extremal values of E, and the characteristic itself reflects a sort of hysteresis: striking of the arc occurs at a lower value of the current and a higher voltage than quenching. This effect is well known in connection with the burning of an ac arc. Restriking occurs in the heated gas. In this case the restriking potential is always higher than the quenching potential [6]. Obviously, the same effect also occurs in connection with the shortening of an elongated arc. In this respect it is understandable that at the moment of shortening the arc should continue to burn for a certain time in the old channel, since in the elongated section the quenching potential has not yet been reached, whereas at points on the loop in the region of the heated gas the striking potential has already been attained. The same hysteresis effect can also be used to explain the dependence, for example, of the stationary arc current on gas flow rate (Fig. 3). Here again we can detect the presence of critical values of the flow rate, for striking and collapse of the arc, $I_s < I_c$.

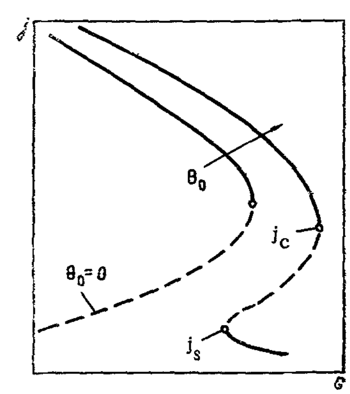

Fig. 3. Arc current as a function of gas flow rate.

Thus, the principal qualitative characteristics of the burning of an electric arc find a simple explanation in the nonlinear temperature dependence of the plasma conductivity. As for approximate quantitative relations, the expressions presented can be used to estimate critical values of the voltage, etc. A more accurate comparison is rendered difficult by the lack of reliable experimental data and the presence of a number of secondary effects.

NOTATION

Q_1 is the power removed from the arc; Q_2 is the heat, in joules; G is the gas flow rate (per second); c_p is the specific heat at constant pressure; α is the heat transfer coefficient; S is the surface area of arc discharge; T is the temperature of arc discharge plasma; T_0 is the temperature of oncoming gas flow; V is the arc voltage; I is the arc current; R is the resistance of the arc column; e is the electronic charge; V_i is the gas ionization potential; and k is Boltzmann's constant.

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