CERTAIN RESULTS FROM A STUDY OF THE ENERGY CHARACTERISTICS OF ELECTRIC-ARC PLASMA INSTALLATIONS

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We study the energy characteristics of an electric-arc plasma installation which is treated as an energy system containing a power source and a plasmatron. We present the energy characteristics of the electric-arc plasma insulation, derived by calculation and experimentally.

Until now, the literature contained virtually no papers devoted to an investigation and analysis of the energy characteristics of electric-arc plasma installations. The closest approach to this problem was undertaken by the authors of [1]. Most frequently, it was the energy characteristics of the plasma device alone that were investigated, i.e., the energy characteristics of the plasmatron [2-3].

We have studied an electric-arc plasma installation as a system containing a power source (with a rigid external characteristic), a plasmatron, a ballast resistance, and current-carrying conductors (wiring, make-and-break contacts); we studied some of the energy characteristics of this system. The case under consideration is the most general; the operation of an electric-arc plasma installation without a ballast resistance, when the plasma arc exhibits a rising current–voltage characteristic, should be treated analogously, assumming $R_b = 0$.

A simplified diagram of the experimental installation is shown in Fig. 1. The plasmatron used in this investigation was hooked up to the "arc" circuit. Argon served as the plasma-forming gas; the gas was fed in tangentially. The current in the circuit was varied by means of the ballast resistance R_b (regulation in stages), and provision was made for stable burning of the arc.

The following quantities were determined during the experiment: the current I in the circuit; the arc voltage U_a; the power source voltage U; the resistance R_{pr} of the current-carrier circuit; and the ballast resistance R_b for each case.

Let a plasmatron be connected to a dc network whose voltage is U = const, with the plasmatron intended as a consumer of electrical energy. The equivalent circuit for this case is shown in Fig. 2. For the static regime the total circuit resistance is given by

$$R_\Sigma = R_b + R_{pr} + R_a \quad \text{or} \quad R_\Sigma = R_l + R_a,$$

where R_l is the resistance governing the loss of power in the electric circuit, and R_a is the resistance of the plasma arc.

Let us make the approximate assumption that the resistance R_{pr} of the current-carrier is constant throughout the entire period of operation for the installation. The plasma-arc resistance R_a, representing one of the most important quantities for the electric-arc plasma installation, is variable.

From an examination of the conditions for stable electric-arc burning [4] it follows that the ballast resistance must be a variable quantity. This statement serves to complicate the problem under investigation.

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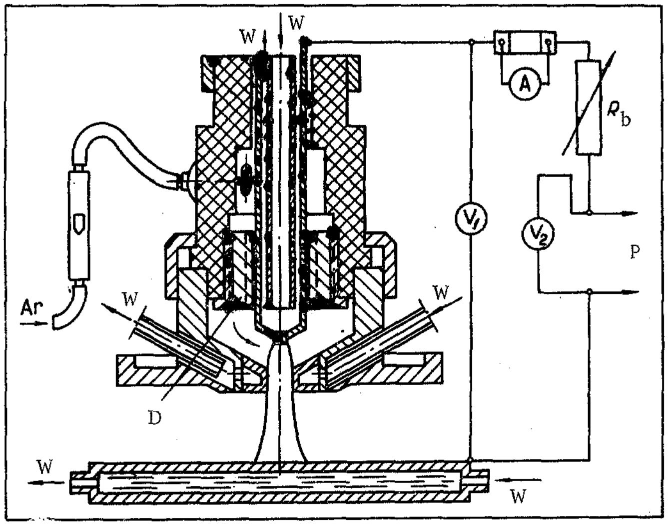

Fig. 1. Design of the plasmatron and its circuit: W) water; D) diaphragm to twist gas flow; P) to power source.

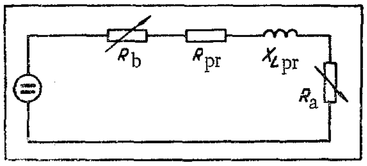

Fig. 2. Equivalent electric circuit for the electric-arc plasma installation.

Therefore, let us initially examine the case in which R_b = const ≠ 0 and R_a = var. The stable burning of the air can be ensured by altering the arc resistance R_a, intensifying the compression of the arc as a consequence of an increase in the flow rate for the plasma-forming gas or by reducing the length of the arc.

The problem in this case reduces to an examination of the current circuit powered by a constant voltage U and total current I, passing through the variable total resistance.

The ratio between the component parts of the total resistance R_Σ is not constant; it varies as a function of the operating conditions in each individual case, and at each separate instant of time.

The current I in the circuit being examined, given a constant network voltage, represents a function of the variable total resistance which, in turn, is determined by the resistance of the arc, i.e.,

$$I = \frac{U}{R_\Sigma} = cf\left(\frac{1}{R_\Sigma}\right). \tag{1}$$

The total power P used from the network is thus a simple function of the current

$$P = UI = cf(I) \tag{2}$$

and is therefore graphically represented by a straight line (Fig. 3).

The lost power determined from the constant resistance R_l is a quadratic function of the current; graphically, this is a parabola (Fig. 3).

The useful power P_a is the difference between the power P taken from the network and the lost power P_l, i.e.,

$$P_a = P - P_l = UI - I^2R_l = I^2(R_\Sigma - R_l) = I^2R_a. \tag{3}$$

Since P and P_l, or the resistances R_Σ or R_l governing these powers, change in accordance with various laws, the useful power P_a as a difference depends in each case on the relationship between the powers (curve P_{a3} in Fig. 3).

The curve showing the useful power exhibits singularities which correspond to the limit cases of operation – no-load and short-circuit regimes.

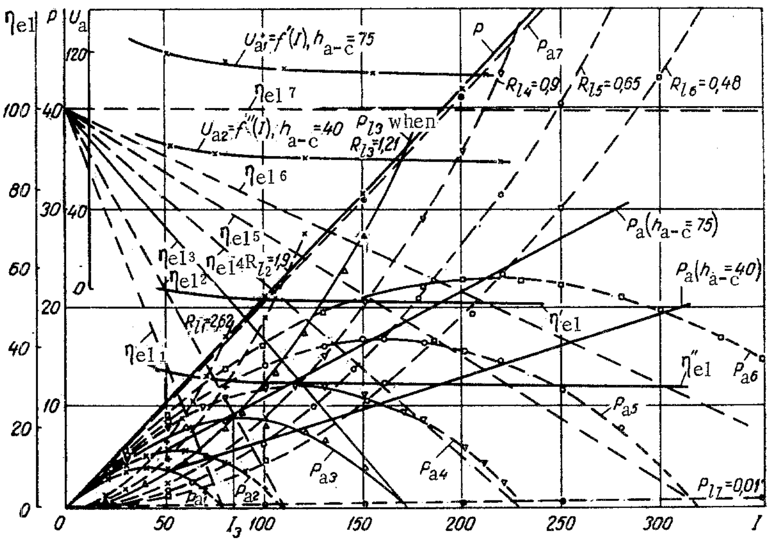

Fig. 3. Characteristics of the electric circuit of the electric-arc plasma installation: η_{el}, %; P, kW; U_a, V; I, A; h_{a-c}, mm.

Here we examine the operation of an electric-arc plasma installation, with the resistance of the plasma arc varying within wide limits.

1. In the case of an infinitely large total circuit resistance, determined by an infinitely large arc resistance, there is no current in the circuit – we are dealing with a no-load regime:

$$R_a = \infty,\ I = 0,\ P = 0,\ P_l = 0,\ P_a = 0.$$

2. We can also have a regime in which the electrodes of the plasmatron are in contact with each other – a short-circuit regime:

$$R_a = 0,\ I = I_c,\ P = P_l,\ P_a = 0.$$

Between these extreme cases, governed by the magnitude of the arc resistance, there exists a value of R_a such that the power generated in the plasma arc reaches its maximum value.

Let us determine the condition under which the plasma-arc power ($P_a = I^2R_a = U^2R_a/(R_p + R_a)^2$) attains its greatest value; for this we must equate the first derivative dP_a/dR_a to zero. After solution of the equation $dP_a/dR_a = 0$ we find that the maximum value for the power of the plasma arc is reached when $R_a = R_l$, i.e., when the arc resistance becomes equal to the sum of the ballast resistance and the structurally governed resistance of the current-carrier circuit. This regime corresponds to a specific current I_3. With a further increase in the current, the lost power P_l increases continuously, while the useful power P_a falls to zero.

The curve for the useful power P_a, derived on the basis of the above-described method, is a parabola, and this is easily demonstrated by proceeding from the general equation (3):

$$P_a = UI - I^2R_l.$$

Let us rewrite this equation in the following form:

$$I^2 - \frac{U}{R_l}\,I + \left(\frac{U}{2R_l}\right)^2 = -\frac{1}{R_l}\,P_a + \left(\frac{U}{2R_l}\right)^2$$

or

$$-R_l\left(I - \frac{U}{2R_l}\right)^2 = P_a - \frac{U^2}{4R_l};$$

$$P_a = -R_l\left(I - \frac{U}{2R_l}\right)^2 + \frac{U^2}{4R_l},$$

and this is the equation for the parabola $y = ax^2 + c$. The axis of this parabola is vertical, but the apex does not lie at the coordinate origin, but at the point x_0, y_0: $x_0 = I_k/2$; $y_0 = P_k/4$.

However, since $I_k = U/R_a$ and $P_k = U^2/R_l$, the curve for P_a over its entire extent is uniquely defined by the values of R_l and U.

Since the useful power is a varying quantity and has a maximum value in some regime, the nature of the variation in this quantity exerts significant influence in operation on the energy indicators of the entire electric-arc plasma installation.

In working with the electric circuits of an electric-arc plasma installation, one of whose elements is the electric arc – burning in the plasmatron – we can speak of an electrical efficiency of the system, assuming the arc power P_a to be useful.

Thus, the electrical efficiency is the ratio that exists between the power fed to the plasmatron and the total used power P, i.e.,

$$\eta_{el} = \frac{P_a}{P} = \frac{P_a}{P_a + P_l} = \frac{UI - I^2R_l}{UI} = 1 - \frac{R_l}{U} I. \tag{4}$$

Here P_l denotes the losses in electrical power.

The electrical efficiency of the electric-arc plasma installation is a function of several quantities: it is a function of the change in the load current I, a function of the network voltage U, of the resistance of the current-carrying conductor, and of the ballast resistance.

If we plot the nature of the variation in the electrical efficiency in Fig. 3 as a function of the current I, we obtain a straight line which intersects the axis of ordinates (here we plot the values of η_{el}) at point 1, while the axis of abscissas is intersected at the point $I = U/R_l = I_k$ (from formula (4)), i.e., at the point which corresponds to the short-circuit current. We see from the graph that the electrical efficiency diminishes with an increase in load and tends toward zero along the straight line, reaching that level in the case of a short circuit.

With low P_a and comparatively small currents, the value of η_{el} is rather high; it drops to a value of $\eta_{el} = 0.5$ for a maximum value of $P_{a\,max}$, and then, as the absolute value of the useful power diminishes, the efficiency also diminishes. We can see from Fig. 3 that two values of η_{el} correspond to each point for P_a; one of the values is better and the other is worse, depending on whether or not the operation is being performed on the ascending or descending branches of the curve for the useful power P_a.

The energy characteristics (the fine solid lines) in Fig. 3 were obtained for $R_b = 1.2\ \Omega$, $R_{pr} = 0.01\ \Omega$ and, consequently, for $R_l = 1.21\ \Omega$. Only certain segments of these curves were derived experimentally, but if the arc were to burn over the entire range of variation in current, which is basically possible, it might be possible experimentally to obtain completely the relationship shown in Fig. 3.

Here we consider the case of an electric-arc plasma installation operating at a constant value for R_l in order to understand how the energy characteristics of the installation vary under conditions of normal use, when R_b = var and, consequently, R_l = var.

Since the current–voltage characteristic of a plasma arc at low currents is clearly one that is declining, the burning of the arc is possible with a substantial ballast resistance. With an increase in the current we find that the current–voltage characteristic gradually changes to become independent of the current, and even changes into a rising characteristic for large current values. This change in the nature of the current–voltage characteristics is governed by R_b which ensures the stable burning of the arc [4].

Figure 3 shows the energy characteristics of an electric-arc plasma installation for various values of R_b, similar to the case considered above; segments of the P_a curves (solid lines) have been obtained experimentally. Here we also show the experimental current–voltage characteristics of an argon plasma arc with lengths of 75 and 40 mm at a constant gas flow rate of G = 20 liters/min. These characteristics correspond to a change in P'_a and P''_a, as well as in η'_{el} and η''_{el}.

This diagram gives us a clear picture as to the distribution – among separate circuit elements – of the electrical power taken from the source and it enables us to establish the existing quantitative relationships for a wide range of variation in R_a and R_l.

For large currents, when the current–voltage characteristic is virtually parallel to the I axis, it is possible to operate with small values for R_b, and as a consequence we have a redistribution of the powers: there is a pronounced increase in the arc power (P_{a5}, P_{a6}) as a result of a reduction in the power losses, and this in turn leads to an increase in the electrical efficiency, i.e., η_{el_5} and η_{el_6}.

It would be interesting to examine the special case in which the installation is operating without a ballast resistance ($R_b = 0$), which is possible if the current–voltage characteristic for the arc is rising. The resistance of the losses is then equal to the resistance of the current-carrying conductors; the latter is insignificant. As a result there is a pronounced reduction in the power loss (P_{l_7}), the plasma-arc power increases (P_{a_7}), as does the electrical efficiency (η_{el_7}),

Earlier we considered an electric-arc plasma installation, one of whose elements is a plasmatron, itself an electric-arc plasma installation. We will not dwell here on the energy characteristics of the plasmatron, but will only indicate the method of determining its efficiency, since this is needed for the determination of the efficiency of the entire electric-arc plasma installation.

The electrical power supply to the plasmatron is converted within the plasmatron into heat, but there is some loss of power in this case, so that the plasmatron is characterized by its own efficiency η_p which is defined as

$$\eta_p = \frac{P_0}{P_a}, \tag{5}$$

where P_a is the power supplied to the plasmatron and P_0 is the power released by the plasmatron.

The power generated by the plasmatron, P_0, is used for various industrial processes, which differ in their nature and in the effectiveness with which the power of the plasma arc or jet is utilized. The effectiveness of utilization for the power generated by the plasmatron will be characterized by the process efficiency η_{pr}, i.e.,

$$\eta_{pr} = \frac{P_{use}}{P_0}, \tag{6}$$

where P_0 is the power generated by the plasmatron and P_{use} is the usefully employed power.

The total efficiency of the electric-arc plasma installation is therefore defined as the product of the electric-circuit efficiency η_{el}, the plasmatron efficiency η_p, and the process efficiency η_{pr}, i.e.,

$$\eta_{tot} = \eta_{el}\eta_p\eta_{pr}. \tag{7}$$

The proposed method of determining the efficiency of the electric-arc plasma installation enables us to evaluate the economy of the electric-arc plasma installation as a whole, as well as for each separate element of that installation, thus enabling us to determine means of raising its operational economic efficiency.

The main effort, until recently, has been directed at the design of better plasmatrons (improving η_p) and at the execution of the technological process (raising η_{pr}).

A study of the manner in which the electrical power taken from the source is distributed among the separate elements of the electrical system enables us to determine the value of η_{el}, which is quite low in existing electric-arc plasma installations (no more than 50%).

Analysis of the energy characteristics for the electric-arc plasma installation enables us to establish the parameters governing η_{el}; these parameters include the voltage of the supply network, the operating current, the magnitude of the resistance of the current-carrying circuit and that of the ballast resistance, if such exists.

Thus we are confronted with the problem of choosing a working voltage and an optimum current for the electric-arc plasma installation, and these parameters, in turn, govern the choice of the power source.

NOTATION

I	is the current in the circuit of the electric-arc plasma installation;
I_{sc}	is the same, in the short-circuit regime;
U_a	is the voltage at the plasma arc;
U	is the voltage of the power source;
P	is the power used by the installation;
P_a	is the power of the plasma arc;

P_l is the power lost in the electric circuit;
P_{sc} is the power required by the installation in the short-circuit regime;
R_a is the resistance of the plasma arc;
R_b is the ballast resistance;
R_{pr} is the resistance of the current-carrying conduits;
R_l is the resistance governing the power loss in the electric circuit;
R_Σ is the total resistance of the electric circuit;
η_{el} is the electrical efficiency;
η_p is the plasmatron efficiency;
η_{pr} is the process efficiency;
η_{tot} is the total efficiency of the electric-arc plasma installation.

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