GENERALIZATION OF THE CURRENT-VOLTAGE CHARACTERISTICS OF GEOMETRICALLY DISSIMILAR ARC HEATERS

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It is shown that the current-voltage characteristics of linear, geometrically dissimilar arc heaters with vortex nitrogen stabilization can be generalized by means of a single expression.

In arc heaters the thermal and electrical effects are closely related. Heat transfer between the arc and the stabilizing gas has a strong influence on the electrical processes, while, in its turn, the heat transfer depends on the arc burning conditions.

A theoretical examination of this complex picture is extremely difficult. Therefore, in some recent studies [1–4] an attempt has been made to develop methods of calculating arc heaters by generalizing their characteristics by the method of approximate similarity. The similarity criteria are determined from those processes on which the effect in question chiefly depends. As far as electric arcs are concerned, the basic process is that of heat transfer between the arc column and the surrounding medium. The principal characteristic criterion for this process is the number $\mathrm{Ku} = Gd\sigma_0 h_0/I^2$, which is easily obtained from the arc energy balance equation [2]. In many instances this characteristic criterion alone is used in generalizing the current-voltage characteristics of stabilized arcs. In particular, it is used in connection with certain types of linear heaters with vortex gas stabilization [1, 2].

The generalized current-voltage characteristic of such a heater has the form

$$Ud\,\sigma_0/I = f\,(I^2/Gd\,\sigma_0\,h_0), \tag{1}$$

or in dimensional form for some specific gas

$$Ud/I = f\,(I^2/Gd). \tag{1a}$$

In expression (1a), as distinct from expression (1), the characteristic values of the physical properties σ_0 and h_0 are assumed constant. The Re and Kn numbers were also used in [3] for generalizing the characteristics of arc heaters with vortex gas stabilization.

The data presented in [1–3] relate to arc heaters with similar discharge chamber geometry. Practical requirements often lead to departures from the investigated geometry.

To ascertain the effect of arc heater geometry on the current-voltage characteristics we conducted experiments on a linear heater with vortex nitrogen stabilization. The apparatus was similar to that described in [5]. The closed electrode was the cathode, the open electrode the anode. The apparatus was so designed that any combination of electrodes 1, 2, and 4 cm in diameter could be obtained.

The effect of the absolute value of the diameter was investigated on apparatus with identical anode and cathode diameters (D = d), i.e., at electrode diameters of 1, 2, and 4 cm.

The current-voltage characteristics of the discharge chambers were recorded at different gas flowrates (2, 4, and 6 g/sec). The results of the experiments are shown in Fig. 1a.

As can be seen from the graph, the arc voltage depends both on the gas flowrate and on the diameter of the discharge chamber. It increases strongly with increase in gas flowrate. The increase in arc voltage with increase in discharge chamber diameter is less pronounced.

An increase in the inside diameter of the electrode leads to a fall in gas velocity and hence to a decrease in the voltage gradient in the arc column. If the arc length were to remain constant, the arc voltage would fall in proportion to the gradient. In reality, the arc voltage does not decrease, but increases. This can only be attributed to elongation of the arc.

A change in arc length as a function of the discharge conditions is a characteristic feature of linear gas-stabilized arc heaters. The reason for this effect is that in such equipment the linear dimensions of the arc depend on the conditions of electrical breakdown of the cold layer of gas adjacent to the electrode. Other things being equal, as the electrode diameter decreases, the fraction of the channel cross section occupied by the arc increases. The heating of the layer of gas near the wall is correspondingly greater, and the breakdown voltage lower. Accordingly, as the electrode diameter decreases, the arc shortens, and the voltage decreases, the fall in voltage predominating over the increase in electric field intensity. Varying the electrode diameter leads to a stratification of the generalized current-voltage characteristic (Fig. 1b).

In order to take into account the process of breakdown of the layer of gas in the region of the electrode wall, it is necessary to introduce criteria characterizing this effect. In [3] it was proposed to use the Knudsen number, whose reciprocal at constant temperature in dimensional form is proportional to the product of the pressure and the characteristic dimension $1/\mathrm{Kn} \sim Pd$. Consequently, in accordance with Paschen's law, the breakdown voltage depends on the Knudsen number $U_b = f(Pd)$. However, the use of this criterion presupposes that the dependence of the arc voltage on the diameter and pressure is the same. This is not confirmed by experiments on arc heaters with vortex gas stabilization: the arc voltage depends only weakly on the pressure when the other criteria are constant. Apparently, the arc length depends not only on the breakdown conditions but also on a number of other processes which cannot be reflected in a single criterion. If a single gas is employed, when the generalized formulas are reduced to dimensional form, it may be assumed that the diameter represents the dimensional parts of the corresponding combination of certain criteria reflecting the influence of the breakdown conditions on the arc characteristics.

The dependence of the complex Ud/I on the electrode diameter can be obtained by constructing the graph $(Ud/I)/(I^2/Gd)^{-b} = f(d)$, the value of the exponent b being taken equal to 0.69 in accordance with the data of Fig. 1b. It was found that this relation is well approximated in logarithmic coordinates by a straight line, which in linear coordinates corresponds to a power-law relation. The value of the exponent n, found by the method of least squares, is 0.358.

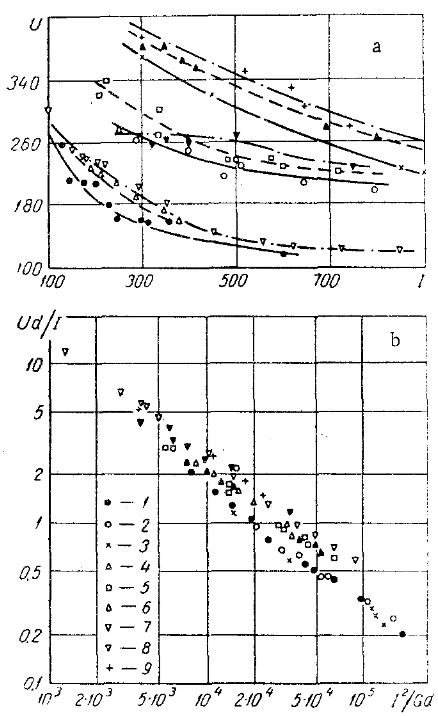

Fig. 1. Nongeneralized (a) and generalized (b) current voltage characteristics of a linear arc heater with vortex nitrogen stabilization: 1, 2, 3) at D = d = 1 cm and g = 2, 4, 6 g/sec, respectively; 4, 5, 6) D = = d = 2 cm, G = 2, 4, and 6 g/sec 7, 8, 9–D = d = 4, G = 2, 4 and 6.

Thus, with allowance for the effect of the electrode diameter with D = d, the generalized current-voltage characteristic of a linear arc heater with vortex nitrogen stabilization assumes the form

$$Ud/I = 1.37\cdot 10^5\,(I^2/Gd)^{-0.69}\,d^{0.36}. \qquad (2)$$

The deviation of the experimental points from the approximating curve calculated from Eq. (2) does not exceed 10%.

Further analysis of experiments conducted on discharge chambers with different electrode diameters in $Ud/Id^{0.36} - I^2/Gd$ coordinates revealed the existence of differences due to inequality of the cathode and anode diameters.

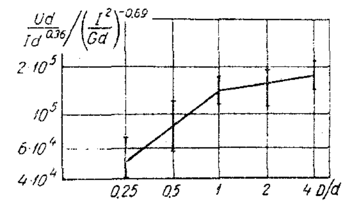

Fig. 2. The complex $Ud/Id^{0.36})/$ $/(I^2/Gd)^{-b}$ as a function of the ratio of electrode diameters.

The dependence of the generalized current-voltage characteristic on the ratio of electrode diameters was determined in the same way as the dependence on the electrode diameter.

It is clear from Fig. 2 that when D/d < 1 the diameter ratio has a much stronger effect on the complex $(Ud/Id^{0.36})/(I^2/Gd)^{-0.69}$ than when D/d < 1. Apparently, this is because an increase in the diameter of the closed electrode has only as slight effect on the elongation of the arc, whereas a decrease makes the entry of the gas into the closed electrode much more difficult, which leads to an appreciable shortening of the arc. If, in order to obtain a convenient formula, one uses a single power-law approximation over the entire interval of variation of diameters investigated, the exponent is found to be equal to 0.2.

In this case, instead of (2), we obtain the expression

$$Ud/I = 1.26\cdot 10^5\,(D/d)^{0.2}\,(I^2/Gd)^{-0.69}\,d^{0.36}. \qquad (3)$$

If the curve is approximated not by one, but by two straight lines (the first from D/d = 0.25 to D/d = 1, the second from D/d = 1 to D/d = 4), the exponent calculated by the method of least squares is 0.34 for the first interval, and 0.07 for the second.

For D/d < 1 the formula assumes the form

$$Ud/I = 1.41\cdot 10^5\,(D/d)^{0.34}\,(I^2/Gd)^{-0.69} d^{0.36}, \qquad (4)$$

and for D/d > 1

$$Ud/I = 1.45\cdot 10^5\,(D/d)^{-0.07}\,(I^2/Gd)^{-0.69}\,d^{0.36} \qquad (4a)$$

The scatter of the experimental points is greater for D/d < 1 than for D/d ≥ 1. These differences cannot be attributed to errors in the measurements or noncorrespondence between the approximating expressions and the actual laws. They are a consequence of the fact that in heaters with D/d < 1 the arc burns unstably with sharp surges of current and voltage. This instability is due to intensification of the flow fluctuations in the closed electrode when its diameter is less than that of the open electrode. In this case the arc spot is not readily entrained into the interior of the electrode; the arc shunting frequency is low; and the arc stays for long periods at the end of the electrode close to the gap. Apart from unstable burning, this leads to local overheating of the electrode surface in the shunting zone and to intensified electrode erosion.

Unstable burning and rapid electrode wear in equipment in which $D/d < 1$ show that the use of such equipment is undesirable. Construction of generalized current-voltage characteristics for configurations in which $D/d < 1$ in the form of the relation $Ud/Id^{0.36} = f(I^2/Gd)$ revealed a difference in gas flowrates due to the effect of the Reynolds number. Therefore, in order to increase the accuracy of the generalized formulas for the discharge chamber configurations in question it is possible to introduce the Re number.

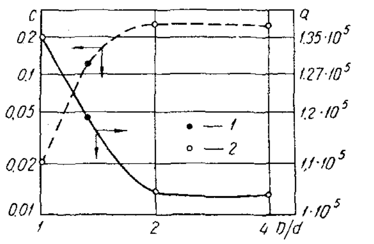

Fig. 3. Exponent c of Re number and coefficient a in Eq. (6) as functions of the ratio of electrode diameters: 1) data of [5], 2) experimental data of authors.

When $D = d$, the influence of the Re number is only slight. However, as the ratio D/d increases, it becomes increasingly important. Figure 3 presents a graph of the exponents of the complex G/d, which in dimensional form (μ_0 = const) is proportional to the Re number, as a function of the ratio of electrode diameters.

The figure shows that the effect of Re number depends strongly on the diameter ratio. The greater D/d, the stronger the effect of the Re number. However, when $D/d > 2$ the exponent of G/d acquires a constant value. Therefore a power-law approximation can only be used for configurations in which $D/d > 2$, it being possible to neglect the effect of D/d in this range (Fig. 3). The formula becomes

$$Ud/I = 1.04 \cdot 10^5 (G/d)^{-0.25} (I^2/Gd)^{-0.69} d^{0.36}. \qquad (5)$$

When $D/d = 1-2$ it is possible to use the formula

$$Ud/I = a (G/d)^{-c} (I^2/Gd)^{-b} d^n, \qquad (6)$$

in which the coefficient a and the exponent c can be taken from the data of Fig. 3. As before, the exponents of the diameter and the complex I^2/Gd are taken equal to $n = 0.36$; $b = 0.69$.

The accuracy of the empirical formulas is increased somewhat by introducing the Re number, and the deviations from the approximating curve do not exceed 50%.

In calculations involving a lower degree of accuracy Eq. (2) is the most suitable, since it contains a smaller number of variables. In the range $D/d = 1-4$ the deviations of the experimental points from the curve calculated from (2) are less than 30%.

Since the characteristics of arc heaters with air stabilization are similar to those of heaters with nitrogen stabilization, formulas (2) and (5) can also be used for calculating heaters in which air is used as the working medium.

NOTATION

I is the current, A, U, are the voltage; V, U_b are the breakdown voltage; G is the gas flowrate; d is the diameter of open electrode; m, D are the diameter of closed electrode; μ is the viscosity; P is the pressure; Kn is the Knudsen number; Ku is the Kutateladze number; σ is the characteristic value of electrical conductivity; h_0 is the characteristic value of enthalpy; b, c, n are the exponents; a is the proportionality factor, $m^{-0.36}$.

REFERENCES

1. S. S. Kutateladze and O. I. Yas'ko, IFZh, no. 4, 1964.

2. O. I. Yas'ko, IFZh, no. 12, 1964.

3. G. Yu. Dautov and M. F. Zhukov, PMTF [Journal of Applied Mechanics and Technical Physics], no. 2, 1965.

4. A. S. Koroteev and O. I. Yas'ko, IFZh [Journal of Engineering Physics], 10, no. 1, 1966.

5. V. L. Sergeev and F. Yu. Yurevich, IFZh [Journal of Engineering Physics], no. 7, 1964.

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