ALLOWANCE FOR GAS-DYNAMIC FACTORS IN THE DESIGN OF ELECTRIC-ARC HEATERS WITH VORTEX GAS STABILIZATION

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Inzhenerno-Fizicheskii Zhurnal, Vol. 10, No. 3, pp. 287–293, 1966

UDC 533.6

The gas-dynamic stability limits of electric-arc heaters have been experimentally investigated and the effect of the principal electrical, gas-dynamic and geometrical factors on arc stabilization is established. A design equation for calculating anode diameter is obtained such that steady vortex stabilization is ensured within the operating range of the heater.

In the last few years electric-arc plasma generators of various types have been extensively developed. Electric-arc devices with vortex gas stabilization of the arc [1–5] have been studied in greatest detail. An attempt has been made to generalize the electrical characteristics of such generators on the basis of the differential equation for the power balance of an arc swept by a high-speed gas flow. From this equation a general form of the criterial equation has been obtained with the aid of similarity theory methods, and for the same gas at the same pressure in the apparatus the following relationship between the dimensional complexes has been proposed:

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

This relationship has been confirmed by the results of experiments with a generator operated at high current density in nitrogen and air. It can be assumed with fair approximation that in an apparatus of this type a column of hot gas at a temperature approximating that of the arc occupies virtually the entire cross section of the anode.

For a high-voltage generator whose working current does not exceed several hundreds of amperes Eq. (1) is inadequate for satisfactory generalization of the experimental data when the generator operates on hydrogen or hydrogen mixtures. For this case we propose in a paper to be published later an improved criterial equation allowing for the relation between the geometrical dimensions of the high-temperature and low-temperature zones in the anode,

$$Ud/I = f\,(I^2/Gd;\ I^{2/3}/d). \tag{2}$$

The experimental data obtained with hydrogen [4] can be satisfactorily approximated by the following equations:

$$Ud/I = 3900\,(I^2/Gd)^{-0.33}\,(I^{2/3}/d)^{-1.0}, \tag{3}$$

$$Ud/I = 4500\,(I^2/Gd)^{-0.33}\,(I^{2/3}/d)^{-1.0}. \tag{4}$$

In explicit form Eqs. (3) and (4) are in good agreement with the form of treatment of experimental data based on dimensional analysis.

Solving Eqs. (3) and (4) for U we have

$$U = 3900\,(I/Gd)^{-0.33}, \tag{5}$$

$$U = 4500\,(I/Gd)^{-0.33}. \tag{6}$$

Equations (3) and (5) apply to devices with a stub cathode, (4) and (6) to devices with a tubular cathode.

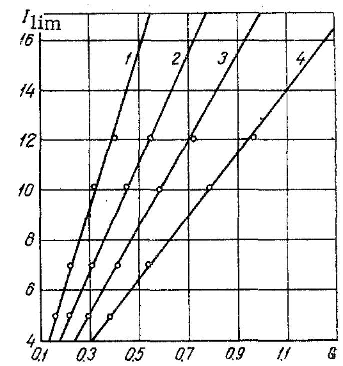

Fig. 1. Limits of stabilization of the arc with respect to current I_{lim} (*a*) and gas flow rate G (g/sec) at electrode diameters d: 1) 10 mm; 2) 15 mm; 3) 20 mm; 4) 30 mm.

The proportionality factors in the equations depend approximately linearly on the distance between electrodes. In the paper to be published we show that in cases of practical importance a distance $0.20\ L_a$–$0.3\ L_a$ between electrodes is selected for the devices considered. Within these narrow limits the voltage correction for the distance between electrodes is not greater than 5% and can be neglected in the calculations. Equations (3), (4), (5), and (6) represent only the power aspect of the process. They are inadequate for designing an electric-arc gas heater since they do not allow for the effect of gas-dynamic factors on the arc-stabilization conditions.

In certain circumstances electric-arc generators with vortex gas stabilization are characterized by unstable operation conditions when the arc discharge is not stabilized by the vortex gas flow on the axis of symmetry of the apparatus. In such cases the gas is virtually unable to draw the arc column into the anode channel. Operation of the heater under these conditions is inefficient. Unstable operation conditions were observed [2, 3, 4] in testing a number of actual geometrical models of electric-arc gas generators.

With the geometrical dimensions of the heater fixed, a certain minimum gas flow, below which vortex stabilization of the arc is disturbed and stable operation becomes impossible, corresponds to each given value of the electric current.

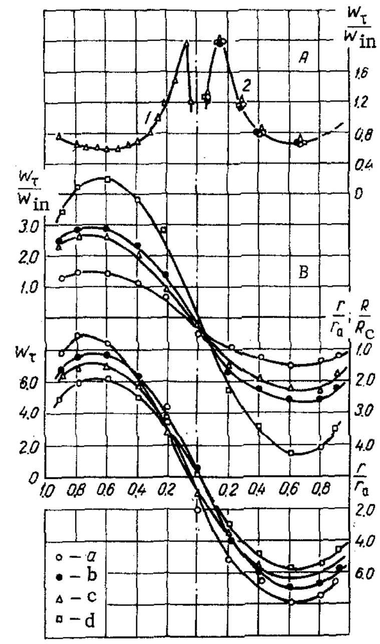

Fig. 2. Tangential velocity distribution curves: A) in the vortex chamber at d = 20 mm, F_{in} = 140 mm^2, n_T = 1 [1) at D_G = 300 mm, G = 9 g/sec, 2) 150 mm and 2.0; 4.2; 6.5; 9.0 g/sec]; B) in the anode channel at d = 20 mm, D_c = = 150 mm, G = 9.0 g/sec [a) at at F_{in} = 140 mm^2 and n_T = 1; b) 140 mm^2 and 2; c) 280 and 1; d) 280 and 2].

The stabilization conditions depend not only on the gas flow and electric current but also on the dimensions of the apparatus. Therefore in designing and modeling electric-arc heaters it is necessary to have at one's disposal a quantitative relationship defining the region of stable operating conditions. The present paper is devoted to an investigation of the gas-dynamic regime of the dc electric-arc heater with a view to obtaining such quantitative relationships.

Experimental investigations were carried out on hydrogen and on air, using apparatus whose construction and electrical and thermal characteristics are described in [4, 5]. In the experiments on hydrogen the limits of transition from stable to unstable operation at different values of the current, gas flow rate, and geometrical dimensions were determined. The stability limits registered by a recording voltmeter from the steep increase in the amplitude of the arc voltage fluctuations. The maximum point on the curves of the function $T_{av.m} = f(G)$ was used as a second indicator.

The gas-dynamic characteristics of the vortex flow in the chamber and in the anode channel were determined by blowing cold air through several models of apparatus of the same type. The tangential and axial velocity distributions were investigated by means of special total and static pressure measuring tubes with 0.8-mm outside diameter. The pressure was measured in the diametral direction at several sections over the chamber and electrode heights.

The investigation was conducted over the following intervals of values of the main geometrical dimensions and gas flow rates: a) vortex chamber diameter: 150 and 300 mm (hydrogen), 150, 300, and 400 mm (air); b) anode diameter: 10, 15, 20, 30, and 40 mm (hydrogen), 10, 20, 30, and 38 mm (air); c) number of tangential inlet nozzles: 1 and 2; d) cross section areas of each inlet nozzle: 140 and 280 mm^2 (hydrogen), 140, 280, 750, and 1350 mm^2 (air); e) gas flow rate, 0.3–1.4 g/sec (hydrogen), 4–54 g/sec (air).

The results (see table) show that if the anode diameter and the distance between electrodes are increased it is necessary to increase gas flow rate in order to ensure stabilization of the arc at a given current. Thus, increasing the electrode diameter from 10 to 30 mm results in an increase in hydrogen flow rate by 50–80%, while if the distance between electrodes is increased from 40 to 60 mm the minimum necessary gas flow rate increases by 15–30%. Substitution of two inlet nozzles for one has no appreciable effect on the stabilization conditions, although the gas inlet velocity is halved. A decrease in chamber diameter from 300 to 150 mm scarcely affected the arc stabilization conditions either. Thus, the anode diameter is the most characteristic of all the geometrical dimensions for stabilization. The distance between electrodes can be varied only within narrow limits, therefore its influence is not important.

The limits of stable operation in Fig. 1 were obtained from the temperature maximum on the curves $T_{av.m} = f(G)$ [4]. The results obtained by both methods are in satisfactory agreement. Over the range of currents investigated the dependence $(I_{lim})_d = f(G)$ is linear in character.

The results of the experiment for measuring the tangential velocity distribution in the vortex chamber (see curves 1 and 2 in Fig. 2, A) confirmed the self-similarity of the vortex flow for apparatus of the cyclone type and showed that the dimensions of the vortex chamber do not appreciably affect the maximum value of the velocity W_T.

Measurements of velocity distribution at different sections over the electrode height showed that the vortex motion remains more or less unchanged to a considerable depth. This made it possible to take the main measurements of the gas-dynamic parameters at all electrode diameters investigated at two sections, namely, at distances of 100 and 200 mm from the gas inlet into the electrode channel, which corresponds to the length of the arc discharge in electrodes 10 and 20 mm in diameter [5].

Minimum Values of Hydrogen Flow Rate Ensuring Stabilization of the Arc

Anode diameter x, mm	Hydrogen flow rate G (g/sec) at current I (a)															
	5				7				10				12			
	Distance between electrodes l_{a-c} (mm)															
	40		60		40		60		40		60		40		60	
	Number of inlet nozzles n_T															
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	—	—	0.3	0.31	0.3	0.32	0.40	0.42	0.44	0.47	0.55	0.58	0.53	0.56	0.66	0.7
15	—	—	0.31	0.33	0.33	0.35	0.43	0.46	0.5	0.53	0.57	0.61	0.59	0.62	0.69	0.75
20	0.3	0.32	0.35	0.37	0.38	0.42	0.45	0.49	0.54	0.59	0.63	0.69	0.65	0.71	0.74	0.81
30	0.33	0.36	0.39	0.44	0.44	0.51	0.5	0.57	0.68	0.74	0.81	0.89	0.81	0.87	0.92	1.05

Figure 2, B (curves a, b, c, d) shows the tangential velocity distribution over the cross section of an electrode 20 mm in diameter at different flow areas of the inlet nozzles and constant air flow rate G = 9.0 g/sec. In a chamber 150 mm in diameter a four-fold increase in the area of the inlet nozzles (decrease in inlet velocity) resulted in a decrease of the absolute tangential velocity $W_{\tau\,max}$ by 40%, while the relative velocity $W_{\tau\,max}/W_{in}$ increased at the same time from 1.5 to 4.6. Thus, variation in the area of the inlet nozzles has a considerable effect on the flow friction of the chamber and the coefficient $\varepsilon = W_\tau r_m/W_{in}R_{in}$ and little effect on the value of the tangential velocity. In our tests the coefficient ε varied from 0.15 to 0.65.

The influence of other geometrical dimensions on the value of maximum tangential velocity in the electrode is shown in Fig. 3. The absolute value of the velocity mainly depends on the diameter of the anode.

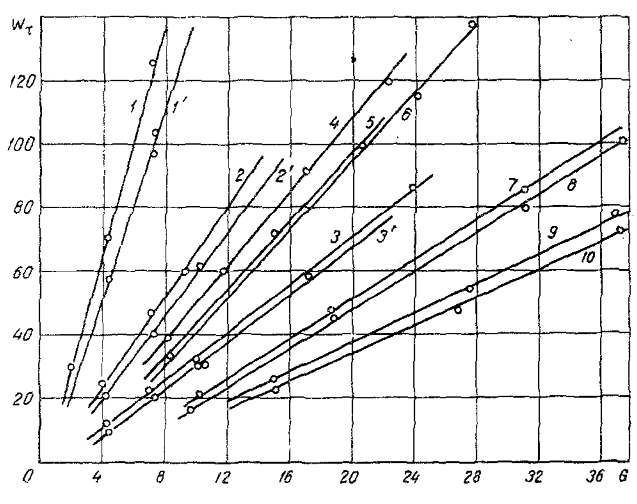

Fig. 3. Dependence of maximum value of tangential velocity W_τ (m/sec) in the anode on air flow rate G (g/sec) and geometrical dimensions: 1, 2, 3) at D_c = 150 mm, d = 10, 20, 30 mm, F_{in} = 140 mm², n_τ = 2; 1′, 2′, 3′) D_c = 300 mm, d = 10, 20, 30 mm, F_{in} = 140 mm², n^τ = 2; 4) at D_c = 400 mm, d = = 20 mm, F_{in} = 750 mm², n_τ = 1; 5) 400, 20, 1350, 1, respectively; 6) 400, 20, 1350, 2; 7) 400, 30, 1350, 1; 8) 400, 30, 1350, 2; 9) 400, 38, 1350, 1; 10) 400, 38, 750, 2.

Tangential velocity and maximum current I_{lim} increase linearly with increase in gas flow rate. The data (1–3 and 1′–3′ in Fig. 3) obtained for the devices

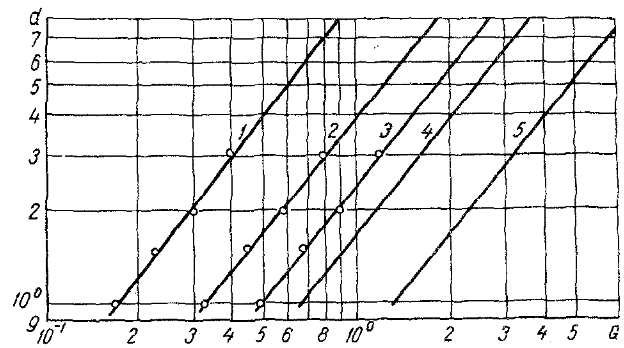

Fig. 4. Dependence of maximum value of anode diameter d (cm) on gas flow rate G (g/sec) and current at the limit of stabilization: 1) at I_{lim} = 5 A; 2) 10; 3) 15; 4) 20; 5) 40.

tested earlier using hydrogen show that doubling the chamber diameter decreases the tangential velocity by only 5–20%. Variation in the area and number of the inlet nozzles (4–10 in Fig. 3) also leads to a variation in tangential velocity by not more than 20%. These results are in good agreement with the data on determination of the limits of stable operation.

Comparisons of the plots in Figs. 1 and 3 show a clear analogy between the dependences of the stabilization limit and tangential velocity on the variation in gas flow rate for apparatus of the same dimensions. At G = const the limiting current and tangential velocity as functions of the electrode diameter are expressed by the same law. These experiments confirm the assumption that stabilization of the arc column is ensured when a certain critical value of the tangential velocity is reached in the anode channel. Thus, it can be assumed that there is a quantitative relationship between the limiting current and the tangential velocity in the anode channel. Direct determination of the critical tangential velocity during operation (when the arc is burning) involves great technical difficulties. However, the indirect experimental data given above (instead of tangential velocity use was made of the gas flow rate at the limit of stability) make it possible to define quantitatively the region of stable operation. At the boundary of the region of stabilization of the arc the relationship between gas flow rate, electrode diameter, and current is expressed in logarithmic coordinates (Fig. 4) by a set of parallel straight lines using these experimental data with extrapolation to a wider region of values of the main parameters.

In analytic form this relationship is approximated by the equation

$$d = 61\,(G/I)^{1.2}. \qquad (7)$$

The constant coefficient and the exponent in Eq. (7) were determined for a hydrogen heater with a stub cathode at a chamber diameter of 300 mm, inlet gas velocity of 30–60 m/sec and a distance between electrodes of 60 mm ($0.25\ L_a$–$0.35\ L_a$).

It was shown earlier [4] that an increase in electrode diameter at fixed values of current and gas flow rate leads to an increase in arc voltage and power. However, as follows from the experimental results, an arbitrary choice of electrode diameter may lead to instability owing to insufficient tangential velocity in the electrode channel. Therefore in designing the apparatus the diameter of the anode must be determined from formula (7), which characterizes the conditions of gas-dynamic stabilization.

Thus, the approximate procedure for the design of an electric-arc gas heater with vortex stabilization can be supplemented by a second basic equation. The third equation necessary for the calculation follows from the given heating power because gas flow rate and temperature are usually governed by the technical requirements, and the thermal efficiency for apparatus of this type varies within narrow limits (0.7–0.9). As a result, values of U, I, d, which ensure stable operation of the heater at a specified heating power, are found by simultaneous solution of the series of equations (6), (7), and

$$N = UI = \Delta HG/0.239\eta. \qquad (8)$$

As experience shows, it is desirable to vary the other basic geometrical dimensions of the apparatus (diameter of vortex chamber and cathode, number and size of inlet nozzles, length of electrodes) within comparatively narrow limits. In this connection they are chosen mainly from constructional considerations, and, when necessary, their effect is allowed for by introducing constant coefficients into the basic equation.

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1 June 1965