DESIGN OF AN ARC HEATER WITH DISCHARGE STABILIZATION BY A GAS EDDY

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General electrical and thermal characteristics are presented for an arc heater of this type.

Here we describe a method of calculating the basic characteristics of a linear arc heater with self-adjustment of the arc length (Fig. 1), for which purpose we use experimentally defined relationships between the basic parameters.

Numerous voltage—current curves have been described [1-10] for heaters of this type for air and nitrogen, and it has been found [9] that the most probable values for the coefficients in

$$Ud/I = A(I^2/Gd)^{-n} \tag{1}$$

are A = 935 and n = —0.7 for I^2/GD from $3 \cdot 10^2$ to $3 \cdot 10^5$ A^2 sec/g·cm.

The overall ranges for the parameters in the formulas were as follows: I = 10-2000 A, G = 0.5-30 g/sec, d_c = 10-40 mm, d = 8-40 mm, p_{pc} = 10-30 N/cm², l = 50-160 mm, l_c = 80-110 mm (the anode length l, the cathode length l_c, and the gap between the electrodes and various other quantities are not given in all papers).

The discrepancies between the formulas given by different workers exceed the corrections introduced in certain papers into (1), so they were neglected in the formula given here.

We checked (1) for the following ranges: power input 40-300 kW, current 100-1200 A, nitrogen flow rate 2-12 g/sec, channel diameter in anode 10-30 mm, and pressure in discharge chamber 10-15 N/cm². There was no substantial effect on the voltage—current characteristics from changing the internal diameter of the gas ring from 44 to 86 mm, the gap between the electrodes from 1 to 7 mm, the number of holes for gas inlets (1 or 2), and the corresponding gas flow speed at the inlet of 6 to 35 m/sec.

The error in the relationship of (1) is about 15% for systems with power inputs from tens to hundreds of kW working the above range of parameters.

The curves calculated from (1) for constant G are bounded; the upper boundary is due to displacement of the spot from the channel in the anode at a particular voltage U_B for a given gas flow rate. The lower boundary rises from entry of the discharge into the gap between the electrodes when the gas flow rate is reduced. In that case, it is impossible to work the system in a stable fashion.

Measurements [10] show that the gas annulus diameter and number of gas inlet holes do not have a substantial effect on the boundaries in the above range; the lower boundary moves to higher voltages as the gap between the electrodes increases, while there is less effect on the upper boundary. When the gap is 1 mm, the above relationships do not apply on account of the effect of surface roughness in the gap region. The internal diameter of the hollow anode has more effect on the upper limiting curve, the latter shifting to higher voltages as the diameter increases.

The following relationships describe the boundaries for the above conditions:

$$\frac{U_u}{U_{xx}} = 0.055G^{0.21}(d+7), \tag{2}$$

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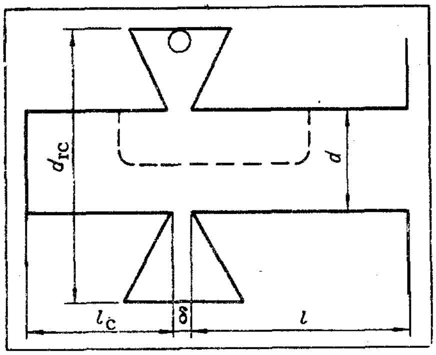

Fig. 1. Eddy-type arc heater.

$$\frac{U_1}{U_{xx}} = 0,06(G + 6\delta + 1), \tag{3}$$

where d is anode diameter in cm, δ is the gap between the electrodes in cm, and G is in g/sec. Lengthening the anode from 100 to 200 m causes U_u to increase by 15-25% at a constant current.

Published data [2, 3, 11-15] for the limits for similar heater systems agree satisfactorily with calculations from (2) and (3) (Fig. 3 of [10]).

Equations (1)-(3) enable one to calculate the permissible input power; to determine the parameters of the hot gas one needs to know the efficiency of the heater.

The published evidence [16-21] for the efficiency of such heaters shows that η is a function of the following parameters:

$$\eta = f(I, G, d, l, p, G_1, \ldots), \tag{4}$$

as well as being dependent on the design features of the heaters.

If one uses the main quantities in (4), one can construct formulas for the efficiency without resort to experimental data by employing the laws for subsonic and transsonic flow with approximate analytical expressions for the gas density as a function of enthalpy.

The following is [22] the expression for the efficiency for transsonic flow of a nitrogen plasma:

$$\eta = 0.793 \cdot 10^{-3} p^{2.94} G^{-1.94} N^{-1} d^{5.85}, \tag{5}$$

where the pressure p · 9.81 in the chamber is in N/cm^2, G is in kg/sec, d in cm, and N in kW.

Experiments [22] at pressures up to 100 N/cm^2 were made with the discharge chamber, and it was found that (5) agrees well with experiment.

No particular scheme for the heater was involved in deriving (5), so the formula applies for any electric arc heater provided that the gas speed equals the speed of sound in the narrow section of the nozzle.

Similar relationships can be derived when there is subsonic flow from the heater nozzle.

For nitrogen at 9.81 N/cm^2, the density in g/m^3 is given for the range from 3000 to 8000°K with an error not exceeding 4% by

$$\rho = 14.8 \cdot 10^3 h^{-0.605}, \tag{6}$$

where the enthalpy h is in J/g; the following is the density of argon at atmospheric pressure between 270 and 10,000°K to 5.6%:

$$\rho = 24.6 \cdot 10^4 h^{-1}; \tag{7}$$

while the density of hydrogen between 500 and 5000°K is given with a maximum error of 12% by

$$\rho = 4 \cdot 10^4 h^{-0.763} \tag{8}$$

and for the range from 4000 to 14,000°K with an error up to 6.6% by

$$\rho = 7.95 \cdot 10^6 h^{-1.2}. \tag{9}$$

We substitute (6)-(9) into Bernoulli's equation and use the fact that G = ρwf and η = Gh/N to get

$$\text{Nitrogen } \eta = 236 (p - p_*)^{1.65} d^{6.6} G^{-2.3} N^{-1}; \tag{10}$$

$$\text{Argon } \eta = 30.5 (p - p_*) d^4 G^{-1} N^{-1}; \tag{11}$$

$$\text{Hydrogen } \eta = 97 (p - p_*)^{0.832} d^{3.33} G^{-0.655} N^{-1}, \quad T = 4000 - 14000^\circ \text{K}, \tag{12}$$

where p is the pressure in the discharge chamber in N/cm^2, d is the nozzle (anode) diameter in cm, and G is in g/sec. Formulas (10)-(12) have been written for the pressure at the exit from the nozzle p∗ of 9.81 N/cm^2; in the more general case of a pressure differing from atmospheric, (11), for instance, takes the form

$$\eta = 3.1 (p - p_*) d^4 p_* N^{-1} G^{-1}. \tag{11a}$$

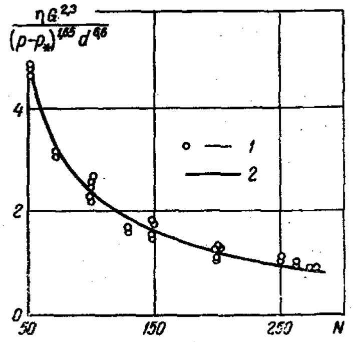

Fig. 2

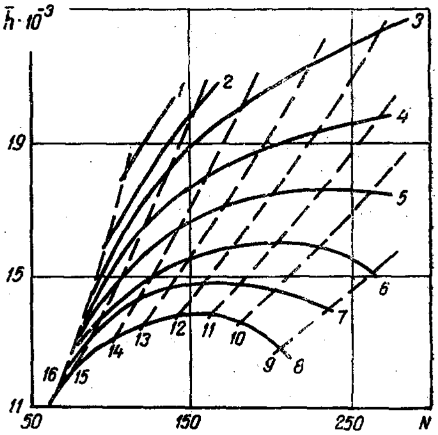

Fig. 3

Fig. 2. Efficiency of subsonic heater: 1) experimental points; 2) calculation (N in kW).

Fig. 3. Characteristics for estimating the optimal anode length for the heater. Solid lines for constant anode lengths l (mm) of: 1) 90; 2) 100; 3) 110; 4) 120; 5) 130; 6) 140; 7) 150; 8) 160; broken lines for constant gas flow rates G (g/sec) of: 9) 9.5; 10) 8; 11) 7; 12) 6; 13) 5; 14) 4; 15) 3; 16) 2; d = 20 mm (N in kW).

We check these relationships on an eddy heater with subsonic flow of a nitrogen plasma; the parameter ranges were N = 50–260 kW, G = 3–10 g/sec, d = 1.5; 2.0 cm; $p-p_* = 0.25$–4 N/cm^2. Figure 2 shows that the measurements agreed well with experiment. Formulas (10)–(12) are not restricted to any particular design of heater and apply for the gas temperatures stated for (6)–(9).

If the pressure in the discharge chamber cannot be measured, or when one is designing a new chamber, the heat loss in the heater can be estimated by means of general relationships for heaters of the above design [23] for the following ranges in the parameters N = 40–300 kW, G = 1.8–14 g/sec, l = 50–200 mm, l_c = 80 mm, δ = 1–7 mm, d_{gf} = 44–86 mm, number of gas inlet holes 1 or 2 (hole diameter 4 mm), G/d = 0.09–1.0 g/sec·mm, l/d = 3.3–20, I^2/Gd = 400–45000 A^2 sec/g·mm.

It was found that the electrode loss was not substantially affected by the diameter of the gas annulus, the number of holes, and the gap between the electrodes; the tangential component of the flow speed did not make an appreciable contribution to the energy transport to the channel wall.

The published evidence indicates that the heat loss to the electrode is determined by three main combinations of parameters:

$$\frac{Q_{el}}{N} = f\left(\frac{I^2}{Gd}, \frac{G}{d}, \frac{l}{d}\right). \tag{13}$$

The combination I^2/Gd can be reduced to N/d, which has a significance of the enthalpy of the heated gas for $\eta = 1$, while G/d corresponds to the Reynolds number Re.

The heat loss in the anode falls as G/d increases but increases somewhat with l/d and I^2/Gd [23].

The following are [23] the relationships for the heat loss in the anode and cathode respectively:

$$\frac{Q_{an}}{N} = 0.05\left(\frac{I^2}{Gd_a}\right)^{0,11}\left(\frac{G}{d}\right)^{-0,25}\left(\frac{l}{d}\right)^{0,17} \tag{14}$$

and

$$\frac{Q_c}{N} = 0.141\left(\frac{I^2}{Gd}\right)^{0,06}. \tag{15}$$

The maximum error in these experiments is 18%. The channel diameters in the anode and cathode were identical. If we use an expression of the form of (1), we get from (14) and (15) the following, which do not contain the voltage:

$$Q_{\mathrm{an}} = 2340 I^{0{,}82} G^{0{,}34} d^{-0{,}33} l^{0{,}17}, \quad (16)$$

$$Q_{\mathrm{c}} = 6600 I^{0{,}72} G^{0{,}64} d^{-0{,}36}. \quad (17)$$

These expressions clearly show the contributions from the basic parameters to the discharge-chamber loss.

These formulas agree satisfactorily with the relationship for the efficiency of a linear heater [19]; the discrepancies over the efficiences range from 1.5 to 17% when I^2/Gd varies from 1000 to 27,000 A^2 sec/g · cm.

The parts of the electrodes away from the arc column have an unfavorable influence, because they cause additional losses and reduce the gas temperature near the jet axis.

One can estimate the minimum electrode lengths for a heater with a self-stabilizing arc length if one knows the arc length as a function of the working parameters.

Measurements have been reported [24] on the distance between the spots for an eddy heater with sectional electrodes; the range of parameters was as given above. The position of the arc spot was determined from the distribution of the current and heat fluxes along the length of the sectional electrode. The positions of the peaks for these two quantities coincided satisfactorily under each working condition.

The following expression (accurate to 10-20%) applies for the distance between the arc spots:

$$l_{\mathrm{d}} = -0.435 I + 24 G + 230, \quad (18)$$

where l_{d} is in mm and G is in g/sec.

It was possible to deduce approximately the loss in the arc spot from the distribution of the heat loss along the length of the anode under several conditions (there was a pronounced peak near the spot with equal losses before and after it [24]). The loss from this source was 20-30% of the total loss in the anode in the current range 200 to 800 A.

The following expression defines the effective potential drop near the electrode, which includes the potential drop in the part of the arc transverse to the flow:

$$\Delta U_{\mathrm{eff}} = 0.0171 I + 17.3. \quad (19)$$

From (16)-(18) one can find the thermal characteristics of the heater that relate the dimensions and working parameters to the enthalpy of the hot gas (Fig. 3). The quantity l in Fig. 3 is the minimum anode length, which includes for each working state the length of the anode part of the arc and half the arc shunting region.

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