GENERALIZATION OF CHARACTERISTICS FOR A TWO-CHAMBER ELECTRIC-ARC HEATER

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We present the results from a generalization of the characteristics for a two-chamber electric-arc vortex heater in which air is used as the working fluid. Empirical relationships are proposed for the determination of the current–voltage characteristics and the efficiency for the range of determining parameters under consideration.

A possible means of heating a working fluid to high temperatures is the use of a vortex-stabilized arc in a dc electric-arc heater. Such a heater is made up of a vortex chamber into which the main quantity of working fluid is fed tangentially, and of a tubular cooled cathode with an independence tangential feed of additional amounts of working fluid; the procedure is based on the application of a two-chamber design and the use of a tubular cooled anode through which the heated gas escapes. Despite the extensive use of such heaters in various branches of engineering, there is presently no method for the calculation of their operational parameters. The various theoretical models are based on a number of simplifying assumptions; it is therefore difficult to expect quantitative agreement between experimental and theoretical results. In certain cases agreement can be achieved by refinement of the theoretical relationships, on the basis of experimental data [1]. Considerable progress in the generalization of experimental data has been achieved through application of the theory of dimensionality [2, 3]. These references are primarily devoted to studying one-chamber heaters. The drawback of the one-chamber design is the absence of a controllable, gas-dynamic effect on the cathode segment of the arc, thus resulting in substantial erosion and even destruction of the cathode in certain operational regimes. To eliminate this drawback, we proposed a two-chamber

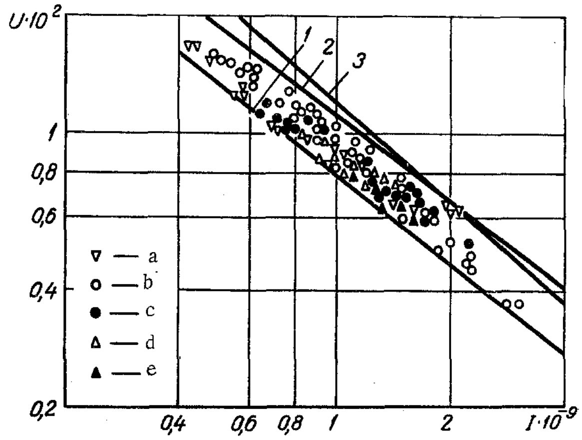

Fig. 1

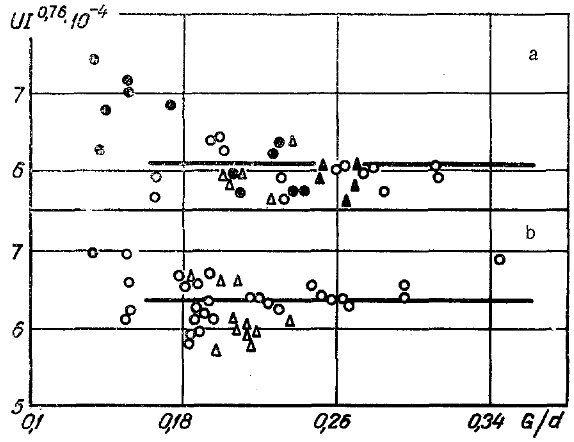

Fig. 2

Fig. 1. Generalized voltage as a function of the generalized current strength: a) $d_*/d = 0.531$; b) 0.5; c) 0.375; d) 0.306; e) 1.0.

Fig. 2. Effect of the parameter G/d on the generalized current–voltage characteristic: a) when $G_1/G = 0.17$-0.22; b) 0.14-0.17.

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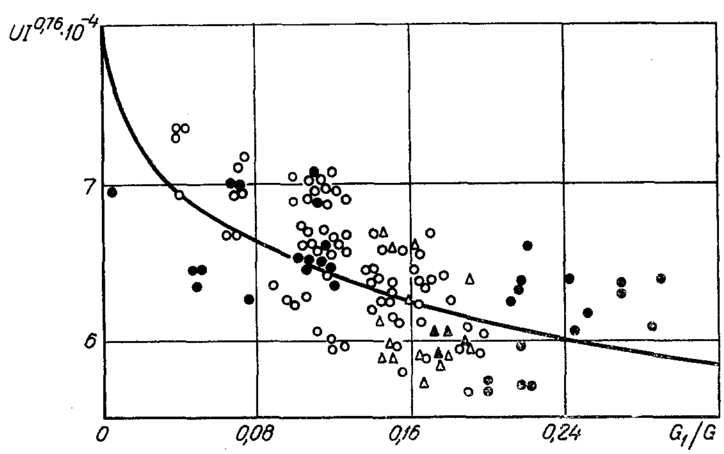

Fig. 3. Effect of the relative flow rate through the cathode on the generalized current–voltage characteristic.

design in which a portion of the flow is fed to the cathode. Certain data on the generalized characteristics of a two-chamber heater are given in [3, 4] (for a fixed ratio between the additional and the main flow).

As follows from dimensionality theory, some arbitrary dimensionless parameter (for example, the dimensionless voltage at the arc, or the efficiency) will be a function of the following basic dimensionless criteria:

$$\frac{i^2}{Gdh_0\sigma_0},\quad \mathrm{Re}=\frac{4G}{\pi d\mu_0},\quad \mathrm{Kn}=\frac{\Lambda}{d},\quad \frac{G_1}{G}$$

for a specific working fluid and for geometrically similar heaters. Bearing in mind that the characteristic values of h_0, σ_0, and μ_0 are constant for the specified gas, we can present these relationships in dimensional form:

$$\Pi_i=f_i\,(I,\ G/d,\ pd,\ G_1/G),\quad I=\frac{i^2}{Gd},$$

in which case

$$\Pi_i=U=\frac{ud}{i},\ \Pi_2=1-\eta,\ \Pi_3=h^*,\ \Pi_4=\frac{d_*}{d}$$

are various dependent parameters. If the discharge from the anode proceeds through a converging nozzle in which the speed of sound is attained, the quantity pd will be determined primarily by the relative diameter of the critical cross section. Instead of the quantity pd it is therefore convenient and possible to use the relative diameter d_*/d of the critical cross section as the determining parameter. The generalized characteristics of the two-chamber heater must therefore be sought in the form of a relationship between the determining parameters U, 1−n, h*, and pd and the determining parameters I, G/d, d_*/d, and G_1/G.

Thus, to obtain the generalized current–voltage characteristic, for example, we have to perform experimental studies for a wide range of variation in four independent parameters. These parametric investigations of a dc heater with a vortex-stabilized arc were performed with air under the following conditions: i = 150–300 A; G = 1.6–5.6 g/sec; d = 0.016 m; p = $(0.7\text{–}3.5)\cdot 10^5$ N/m^2.

Here the independent determining parameters varied in the following ranges:

$$I=(0.5-3)\cdot 10^9\ \mathrm{A^2\cdot sec/kg\cdot m},\quad \frac{G}{d}=0.1\text{–}0.35\ \mathrm{kg/sec\cdot m};$$

$$\frac{G_1}{G}=0-0.3;\ \frac{d_*}{d}=0.3\text{–}1.0;\ pd=(1.1-5.6)\cdot 10^3\ \mathrm{N/m}.$$

The relationship between U and I is shown in Fig. 1, with the various symbols denoting the experimental results achieved at various relative diameters of the critical nozzle cross section. In that same figure we find data for a two-chamber heater at atmospheric pressure and G_1/G = 0.2 [3] (curve 1). For purposes of comparison we have presented the generalized current–voltage characteristics of a one-chamber heater,

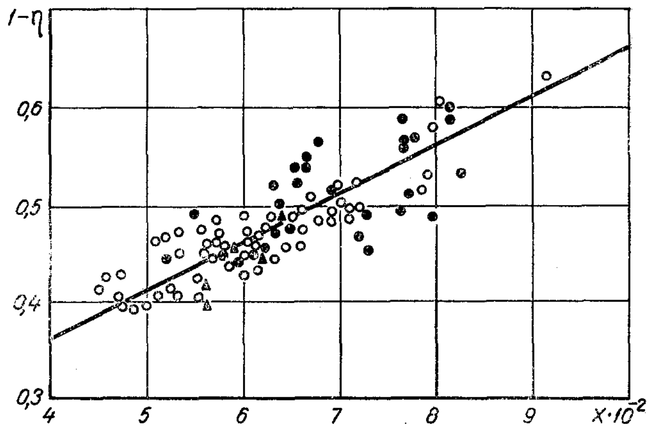

Fig. 4. Magnitude of heat losses in an electric-arc heater.

based on the data of the authors (curve 2) and on the data of reference [3] (curve 3). The experimental results demonstrate that the generalized voltage U is proportional to $I^{-0.76}$, which coincides with the data of [3]. The complex $UI^{0.76}$ may be a function exclusively of G/d, d_*/d, and G_1/G. In Fig. 2 we find the relationship between this complex and G/d for two values of the relative additional air flow $G_1/G \approx 0.15$ and $G_1/G \approx 0.2$. The experimental data derived for various diameters of the critical cross section appear on a single curve, so that we can neglect the effect of d_*/d. With a change in G/d the complex $UI^{0.76}$ remains virtually constant, with the exception of the values of G/d < 0.15, which probably correspond to the laminar flow of the gas in the anode. Indeed, when G/d = 0.15 and the air temperature is 3000°K, the Reynolds number is equal to 2300 and is close to the critical value of the Reynolds number for flow in a tube. If we eliminate from our consideration that their region of small values for the parameter G/d, the complex $UI^{0.76}$ will be an exclusive function of G_1/G. The curve of this function is shown in Fig. 3. Here we also give the calculational results based on the empirical formula

$$U = 8\cdot 10^4 I^{-0.76}\left[1 - 0.4\left(\frac{G_1}{G}\right)^{0.33}\right],$$

which describes the experimental data with an accuracy to ±8%. When $G_1/G = 0$, the characteristics of the heater coincide with the data derived for a one-chamber heater.

The heat losses in the electric-arc heater are the result of physically diverse processes, and it is therefore difficult to assume that the efficiency as a function of the determining parameters can be described by a simple exponential formula. To determine the structure of this relationship, it is advisable to resort to some simple hypothesis that is, however, physically probable. The heat losses in the heater can be divided, in approximate terms, into three types: the convection heat losses Q_1 in the flow of a heated gas; the heat losses Q_2 at the support points of the arc; and the radiative heat losses Q_3. Therefore,

$$1 - \eta = \frac{Q_1 + Q_2 + Q_3}{Q}, \quad Q = ui.$$

The convection losses can be presented in the form

$$\frac{Q_1}{Q} = \frac{4l}{d}\,\mathrm{St} = A,$$

since in the turbulent flow regime the Stanton number is a weak function of Reynolds number, and in the range of variation for the parameter G/d under consideration here may be regarded as constant. The heat losses at the support points for the arc are a function of the sum of the anode and cathode potential drops:

$$\frac{Q_2}{Q} = \frac{\Delta u}{u} = \frac{\Delta u}{UI^{0.5}(G/d)^{0.5}}.$$

At the nearly atmospheric pressures which prevail in the case under consideration, the radiation losses make up a small fraction and therefore $Q_3/Q \ll 1$. Using the expression for the generalized current–voltage characteristic, we can seek the formula for the determination of the heat losses in the form

$$1 - \eta = A + BX, \quad X = \frac{I^{0.26}}{(G/d)^{0.5}\left[1 - 0.4\,(G_1/G)^{0.33}\right]}.$$

This analysis shows that the losses are functions of $(G/d)^{0.5}$ (or of $Re^{0.5}$), and this relationship is not associated with the flow regime (laminar or turbulent). This fact should be borne in mind in analyzing data on the efficiencies of electric-arc heaters. Figure 4 shows results from an experimental determination of

$1 - \eta$, which are truly well described by a formula whose structure is derived from the indicated considerations when $A = 0.16$; $B = 0.5 \cdot 10^{-3}$.

The average mass enthalpy at the outlet from the heater can be found from the formula

$$h^* = UI\eta.$$

It should be stressed that the resulting relationships are valid only for the range of parametric variation considered in this paper.

NOTATION

d	is the anode diameter;
d_*	is the diameter of the critical cross section of the nozzle;
l	is the anode length;
Λ	is the mean free path;
G	is the total gas flow rate;
G_1	is the gas flow rate through the cathode;
i	is the current strength;
u	is the voltage;
Δu	is the sum of the anode and cathode potential drops;
h_0, σ_0, μ_0	are the characteristic values of the enthalpy, the conductivity, and the viscosity, respectively;
h^*	is the stagnation enthalpy at the outlet from the heater;
p	is the pressure;
η	is the thermal efficiency;
St	is the Stanton number.

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