CERTAIN PROBLEMS IN GENERALIZING THE VOLT – AMPERE CHARACTERISTICS OF ELECTRIC ARCS SWEPT BY VARIOUS GASES

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UDC 537.523.5

We demonstrate that the use of criteria reflecting the processes of gas acceleration makes it possible to generalize the volt–ampere characteristics (in dimensionless form) of electric arcs swept by various gases. We have derived a generalized characteristic for an electric-arc heater operating on hydrogen, helium, air, and argon. We discuss methods of raising the accuracy of the generalized characteristics.

A number of recent investigations have demonstrated the inadequacy of a single energy criterion $I^2/GD\sigma_0 h_0$ to generalize the volt–ampere characteristics of swept electric arcs [1-5]. In addition to this criterion, it was proposed in the generalization (in dimensionless form) that use be made of the complexes G/D, PD, $I^{2/3}/D$, L/D, and D/d. Nevertheless, it was impossible to resolve the problem entirely, and the authors of [5] complemented the complexes with introduction into the formula of the electrode diameter d which, in their opinion, represents some, as yet, unknown criterion (or even several criteria).

An interesting attempt to find such a significant criterion is made in [6]. Bearing in mind the effect of the force interaction of the length of the arc in heaters with vortex gas stabilization, the authors introduce the dimensionless complex $\rho PD^4/G^2$ (the analog of the Euler criterion), which corresponded more closely to the experimentally derived relationship between the pressure and the geometric dimensions than did the Knudsen number. By means of the complexes I^2/GD, G/D, and PD^4/G^2 it was possible to generalize the characteristics of a geometrically nonsimilar electric-arc heater, with the influence of the G/D complex weak. This method of determining the reference scales for the physical properties, proposed in [7], was subsequently developed in [8, 9], where the characteristics of a geometrically nonsimilar heater was generalized, this heater operating on hydrogen, helium, nitrogen, air, oxygen, and argon.

Despite the effect achieved, a number of considerations compels us to doubt the expedience of using the criterion $\rho PD^4/G^2$ to generalize the characteristics of electric arcs. The Euler criterion appears in substantial pressure differences, and the criterion $\rho PD^4/G^2$ should play no role in the case of weak ΔP. Nevertheless, it is also effective in the case of small pressure differences across a discharge chamber. Apparently, this simplex is associated, in some way, with other significant criteria. Here it makes sense to check the effect of various dimensionless arguments. This applies primarily to the criterion characterizing the expenditure of Joule heat on the acceleration of the gas in the electric arc.

This criterion can be derived from the energy equation

$$\rho \mathbf{W}\,\mathrm{grad}\,\frac{W^2}{2} = \mathbf{j}E. \qquad (1)$$

Bringing this equation to dimensionless form and bearing in mind that $I \sim jD^2$, and that $G \sim \rho WD^2$, we derive the simplex $\rho^2 I^2 D^3/\sigma_0 G^3$.

Use of this criterion to process the experimental data derived in [8, 9] instead of the complex $\rho PD^4/G^2$ gave results that were not bad. Figure 1 shows the generalized characteristic of a geometrically nonsimilar arc heater operating on hydrogen, helium, air, and argon. The current strength varied from 20 to 920 A; the hydrogen flow rate was 0.5-3 g/sec; that of helium was 0.5-4 g/sec, while that of air was 6-18 g/sec,

Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 16, No. 3, pp. 521-525, March, 1969. Original article submitted June 10, 1969.

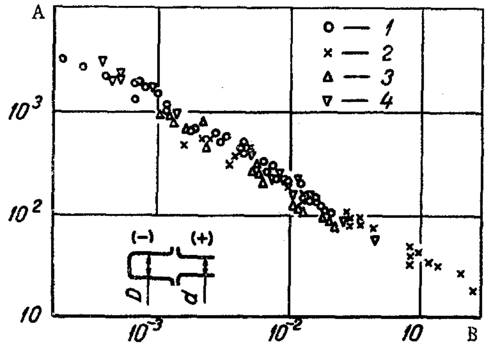

Fig. 1. Generalized volt–ampere characteristics for an electric-arc heater with vortex gas stabilization: 1) air; 2) argon; 3) hydrogen; 4) helium; A) $(UD\sigma_0/I)/(I^2\rho^2 \cdot D^3/\sigma_0 G^3)^{0.15}(h_0/h_{in})^{-0.33}$; B) $I^2/GD\sigma_0 h_0$.

and that of argon was 1-12 g/sec. The diameter of the inside beaker-shaped cooled cathode varied from 14 to 35 mm, while the diameter of the outside cylindrical node varied from 8 to 20 mm. The ratio of the cathode diameter to that of the anode varied from 1.43 to 4.37.

The experimental data were generalized in the form of the relationship

$$\frac{UD\sigma_0}{I} = f\left(\frac{I^2}{GD\sigma_0 h_0},\ \frac{\rho^2 I^2 D^3}{\sigma_0 G^3},\ \frac{h_0}{h_{in}}\right). \tag{2}$$

The decisive values of σ_0 and h_0 were taken from [7], with the density calculated for a temperature corresponding to the values of σ_0 and h_0, subsequently referred to the pressure in the discharge chamber according to the formula $\rho = \rho_0(P/P_0)$. Unlike [8, 9], we have introduced the enthalpy factor h_0/h_{in} rather than the exponent of the approximation curve $\sigma = \sigma_0(h/h_0)^n$ to account for the difference in the temperature relationship with respect to the physical properties of the individual gases.

The scattering of the experimental points with this generalization method is substantially less than when we use the criteria $\rho PD^4/G^2$ and n (±40% as opposed to ±60%). As a result, we find certain significant quantitative relationships. In particular, the points in the figure pertain to two segments which are distinguished by different slopes. The slope of the characteristics with respect to the axis of abscissas amounts to 0.81 to the left of the point $I/GD\sigma_0 h_0 = 2 \cdot 10^{-2}$, while to the right of the point it amounts to 0.63. This fact places in doubt the earlier [7] conclusion regarding the inequality of the angles of inclination for the characteristics of various gases. Indirectly, to some extent, it indicates the validity of the choice of the criteria, since the quantitative relationships should not alter their form as a consequence of the composition of the medium when the phenomena written in dimensionless form are similar.

For the left-hand portion of the characteristic we have $U \sim I^{-0.32}$. Consequently, the left-hand segment corresponds to the descending branch of the volt–ampere characteristic, whereas the right-hand segment pertains to the ascending branch. To be sure, the increase is quite insignificant, and this is a consequence of the reduction in arc length with increasing current. Unfortunately, the right-hand segment is shown only by the argon points, since in operation with other gases the arc was drawn into the gap in this region of operating regimes.

The scattering of the experimental points is a result of various factors. In addition to the experimental inaccuracies and the effect of change in the geometric configuration of the discharge chamber, a substantial role is also played by the approximation errors. In particular, the effect of the enthalpy factor varies with difference values for the criteria $I^2/GD\sigma_0 h_0$ and $I^2\rho^2 D^3/\sigma_0 G^3$. The role of the last criterion depends also on a number of factors. If $I^2\rho^2 D^3/\sigma_0 G^3 < 2$, the exponent for the descending branch in the simplex amounts to 0.1, while for $I^2\rho^2 D^3/\sigma_0 G^3 > 20$ it is doubled. Here we assume an average value equal to 0.15. Since the subject criterion varies by more than 4 orders of magnitude, it has a significant effect on the accuracy of the generalized characteristics. We can reduce the error by selecting more appropriate approximation expressions or by processing the experimental data separately for the various regions within whose limits the extent of the influence of each of the criteria is more or less constant. In this case, it is advisable to provide a separate expression for the right- and left-hand segments of the characteristics shown in the Fig. 1.

For the descending branch we have the generalized formula

$$\frac{UD\sigma_0}{I} = 4\left(\frac{I^2}{GD\sigma_0 h_0}\right)^{-0.81}\left(\frac{I^2\rho^2 D^3}{\sigma_0 G^3}\right)^{0.15}\left(\frac{h_0}{h_{in}}\right)^{-0.33}. \tag{3}$$

The ascending branch is described by the expression

$$\frac{UD\sigma_0}{I}=8.3\left(\frac{I^2}{GD\sigma_0 h_0}\right)^{-0.63}\left(\frac{I^2\rho^2 D^3}{\sigma_0 G^3}\right)^{0.15}\left(\frac{h_0}{h_{in}}\right)^{-0.33}. \quad (4)$$

The arc shunting processes are not accounted for with any special criterion in expressions (3) and (4). With this approximation method, the effect of these processes lies within the limits of accuracy for the formulas. Thus, as follows from the above, apparently the immediate primary problem is improving the methods of approximation and the procefues for the selection of the reference scales f for the physical properties. However, the use of additional criteria can also reduce the error. For example, if the gas is heated in the outside portion of the arc: by the heat released from the arc as a result of heat conduction, which may be the case at low current and limited gas flow rates, and in the case of large electrode diameters, it is advisable to introduce two dimensionless complexes in the place of the criterion $I^2/GD\sigma_0 h_0$, i. e., $I^2/\sigma_0\lambda_0 T_0 d^2$, by means of which we take into account the removal of the power released in the arc column as a consequence of heat conduction, and $Pe = Gcp_0/\lambda_0 D$, which characterizes the heating of the gas by the heat flow. Although the number of independent variables in this case increases, the nature of the process will be reflected more accurately and the accuracy of the formulas must correspondingly increase.

One of the steps to improve the generalization method involves the separate investigation of the descending and ascending branches of the volt–ampere characteristics. To eliminate the additional effect of length, which is found in the case considered above, it is a good idea to examine the intensity of the electric field rather than the voltage at the arc. Thus, in particular, we can determine whether or not the gas-acceleration processes affect only the length of the arc or whether the intensity of the electric field in the arc column is also affected. Unfortunately, as shown by certain investigations [10, 11], significant difficulties are encountered here, and these are caused by the change in the gradient of the voltage over the length of the channel. However, to determine the effect of acceleration on the characteristic of the arc column we can use the data from research on heaters with nonself-adjusting arc lengths.

The characteristics of a plasmatron with a segmented electrode have been studied in [12], and the segmented electrode makes it possible to operate on the ascending branch with a fixed arc length. The initial quantities varied through rather wide limits: $I = 300$-3000 A, $d_c = 1.0$-2.0 cm; $l_{arc} = 7.0$-15.5 cm; $P = 0.05$-0.3 kg/cm^2; $G_{air} = 0.4$-1.5 g/sec.

The authors were unable to generalize the resulting volt–ampere characteristics by using known criteria. However, following [5], they also introduced the electrode diameter d_c as a "representative" of the unknown criteria. The characteristic, generalized in dimensional complexes, was found in the form

$$\frac{Ud_c^2}{l_{arc}I}=5\left(\frac{G}{d_c}\right)^{-1/3}\left(\frac{I^2}{Gd_c}\right)^{-0.4}d_c^{1/3}. \quad (5)$$

Here the current is expressed in amperes, the voltage is expressed in volts, and the remaining quantities are expressed in the above-indicated units.

If we use the criterion $\rho_0^2 I^2 d_c^3/G^3\sigma_0$, we can bring expression (5) to the form

$$\frac{Ud_c^2}{l_{arc}I}=5\left(\frac{I^2}{Gd_c}\right)^{-0.567}\left(\frac{I^2 d_c^3}{G^3}\right)^{0.167}. \quad (5')$$

The result shows that the processes of gas acceleration actually affect the characteristics of a longitudinally swept arc column, while the complex G/d, conversely, has no significance whatever. This was to be expected, since plasmatrons with segmented electrodes operate on the principle of a swept arc, and the Peclet number plays no role. We were also able to eliminate the electrode diameter which is not included in the complexes, as well as being able to reduce the number of independent variables to two.

In studying electric-arc heaters, during the course of the experiments it is convenient to keep the dimensions of the discharge chamber constant, as well as the gas flow rate, changing only the current strength. The simultaneous use of two criteria $I^2/GD\sigma_0 h_0$ and $I^2\rho^2 D^3/\sigma_0 G^3$, both of which contain the term for the current, therefore, substantially complicates the processing of the experimental data. Proceeding from this, in practical terms, in the place of one of the cited generalized arguments it is convenient to use the ratio $G^2/D^4\rho^2 h_0$, while for convenience in calculation it is better to take the square root of this last complex.

Comparison of the resulting complex with the criterion $\rho PD^4/G^2$, as used in [6] to generalize the volt–ampere characteristics of a plasmatron with air stabilization, demonstrates that if consideration is given to the relationship $\rho = \rho_0(P/P_0)$ the volt–ampere characteristics coincide in dimensional form, since ρ_0, P_0, and h_0 are constant in value for a given gas. Therefore, in these generalizations practical provision is made for the acceleration of the gas as it is heated in an electric arc. It thus becomes clear why the generalizations were satisfactory, even in the case of small pressure differences across the discharge chamber.

In dimensionless form these criteria are distinguished by the factor $\rho h_0/P$. Bearing in mind the equation of state, we can bring the dimensionless complex to the form c_{p0}/R. Consequently, these criteria are distinguished only by the values of the reference scales for the molar heat capacities. According to [7], for the gases investigated here, we find the following scale values for the average relative heat capacities: for hydrogen c_{p0}/R equals 10.2; for helium it is equal to 2.88; for air it equals 15.8; and for argon it equals 2.5.

It is found that c_{p0}/R changes by half an order. For biatomic gases it is considerably greater than for monatomic gases. The generalization of the volt–ampere characteristics in dimensionless form, involving the use of the criterion $\rho PD^4/G^2$, therefore must result in substantial differences with regard to the kind of gas. However, by introducing the criterion n, we can smooth out these differences to a considerable extent [8]. Nevertheless, the scatter was considerably greater than in the case of generalization by means of the criterion $I^2\rho^2D^3/\sigma_0G^3$, which in the case of the simultaneous use of the complex $I^2/GD\sigma_0h_0$ is equivalent to the simplex $G^2/D^4\rho^2h_0$.

NOTATION

U	is the voltage;
I	is the current;
G	is the gas flow rate;
W	is the flow velocity;
j	is the current density;
ρ	is the density;
σ	is the electrical conductivity;
h	is the enthalpy;
D and d	are the electrode diameters (major and minor);
P	is the pressure in the discharge chamber;
l_{arc}	is the arc length;
E	is the intensity of the electric field;
c_p	is the heat capacity at constant pressure;
R	is the gas constant.

Subscripts and Superscripts

0	is the reference scale;
c	denotes the cathode;
a	denotes the anode;
arc	denotes the arc;
in	denotes the inlet to the heater;
air	denotes air.

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