Pure & Appl. Chem., Vol. 62, No. 9, pp. 1817–1824, 1990.
Printed in Great Britain.

Some aspects of the generalization of electric arc characteristics

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Abstract - Consideration is given to physical modeling of electric-arc discharges used for generation of technological plasma. The approximate similarity method as applied to the modeling is shown. The main difficulties encountered in generalization of current-voltage characteristics (CVC) in dimensional complexes and dimensionless numbers and the results produced are discussed.

INTRODUCTION

For technological purposes , as a rule, weak-stabilized arcs of complex geometry are used. Mathematical modeling of such discharges runs into essential difficulties. That is why physical modeling is employed especially when it is necessary to design powerful plants.

Rigorous modeling of arc discharges is impossible due to the large number of different physical processes proceeding in them, an account of which will require the use of tens of dimensionless arguments. However, the majority of processes do not exert the pronounced influence on discharge characteristics and they may be neglected. In fact, it is expedient to take into consideration a few dominating phenomena (from one to three) but it is not always possible to reveal them a priori since their relative role changes in dependence on discharge conditions. In practice , different arc-to-heated medium heat transfer processes are the basic ones and a researcher is faced with the problem to choose the most important amongst them as applied to this or that type of an arc.

A choice of scale values of physical properties presents a complicated problem. It is not known at what temperature they should be taken since an arc temperature depends on discharge conditions. Besides, temperature-dependent properties of various media are different. One more difficulty is that concerned with scale determination for arc dimensions since an arc usually occupies only a part of a discharge chamber section and its dimensions also depend on discharge conditions. The similarity of arc and chamber dimensions may violate with a change in the dimensions of the latter. Below the above difficulties to have been overcome are discussed (for details see (refs. 1-6)).

GENERALIZATION OF ELECTRIC ARC DISCHARGE CHARACTERISTICS IN DIMENSIONAL COMPLEXES

Generalized arguments for correlation of arc discharges characteristics may be derived from the energy motion. Thus for a stationary arc $\rho V \nabla h - \nabla(\lambda \nabla T) + Q = \vec{j}\vec{E}$ .Reducing it to the dimensionless form yields $\pi_1 = \sigma_0 h_0 G d / I^2$; $\pi_2 = \sigma_0 \lambda_0 T_0 d^2 / I^2$; $\pi_3 = Q_0 \sigma_0 d^4 / I^2$. Here use is also made of the relationships $G \sim \rho V d^2$, $I \sim \sigma E d^2$ .As a linear dimension scale a discharge chamber diameter , d , is taken. The number π_1 indicates "blowing" by a heated gas, π_2 stands for conductive heat removal of Joule heat, π_3 designates heat removal by radiation. Presently these parameters are also supplemented with $\pi_4 = \rho_0 \sigma_0 h^{1.5} d^3 / I^2$

describing thermal turbulence processes (ref.7). With the simultaneous use of the numbers π_1 , π_2 it may be convenient instead of one of them to use the ratio π_1/π_2 being the Peclet number $Pe = Gc_{p_0}/\lambda_0 d = \pi_5$

In dependence on discharge conditions it may be expedient to change a form of criteria. For instance, for the blowing number the following modifications are possible (refs.1,8): $\sigma_0 h_0 G d / I^2$ (longitudinally blown arc), $\rho_0 h_0^2 \sigma_0^2 B L^5/I^3$ (cross-blown arc); $\rho_0 \mu h_0^2 \sigma_0^2 L^4/I^2$ (an arc moving in its magnetic field); $\rho_0 h_0^2 \sigma_0^2 g L^5/I^4$ (free-burning arc).

Experimental data have been correlated for arc-to-heated gas heat transfer and heat losses to cooled elements of a discharge chamber. For the first case usually arc current-voltage characteristics are correlated since they contain information both on energy exchange and load characteristics of the arc as an electric circuit element. We shall consider the correlation of current-voltage characteristics (CVC) since just these characteristics display the specific features of an electric-arc discharge.

The majority of works concerned with the correlation of arc discharge characteristics is performed traditionally using the power approximations of the form: $F = c \prod_i A_i^{\alpha_i}$ .Here F is the generalized function and A_i are the generalized arguments. As F for CVC the generalized arc resistance is usually used.

Because of the difficulties encountered in the choice of scale values, a larger part of works is performed in dimensional complexes. The essence of the idea is the scale values of properties remain constant for a certain medium and they may be matched with the experimentally determined coefficient c .

The authors of (ref.9) have revealed that the best correlation for longitudinally-blown arcs is obtained when the blowing number is used as the generalized argument. Then for arc CVC we derive the formula $Ud/I = c\,(Gd/I^2)^{\alpha}$

A good correlation in such form is obtained for discharge chambers with a constant diameter. However further works have demonstrated an essential scatter in diameter values. A typical example (ref.10) is shown in Fig.1. The diameter dependence of correlated data is proportional to $d^{0.36}$.

A residual scatter in gas flow rate values is observed in plasmatrons with rod cathodes and two-side efflux. Stratification in the flow rate values is explained by the conductive heat transfer effect, therefore π_2 or π_5 must be used additionally. The conductive heat transfer effect is stronger for high heat-conducting media and very constricted weak-blown arcs. In the limit, for stabilized low-flow rate arcs the CVC correlation is made only with respect to π_2 . As an example, a water-stabilized arc may serve (Fig.2)

For technological purposes of a common use are the blown arcs where the number π_1 is mostly enough to be adopted. Stratification in the diameter values is usually accounted for by arc shunting processes described by the Knudsen number $Kn \sim 1/Pd$. Should all residual stratification in the diameter data be attributed to shunting or not may be answered when comparing plasmatrons with smooth and step electrodes. In the latter large-scale shunting does not occur. Analysis of the generalized characteristics from (ref.11) reveals the diameter dependence at small d when arc is properly constricted. However, as far as a diameter increases, the dependence becomes a mildly sloping curve and at $d > 1$ cm (a 3cm long diaphragm; air) stratification *the diameter values disappears.* In this case the diameter effect is opposite to that in smooth electrodes, i.e. with increasing d voltage falls. Therefore, a researcher should distinguish between the conductive heat removal effect (and probably non-similarity of the arc and electrode dimensions) and the shunting effect. In the apparatus with no shunting π_2 or π_5 while for smooth electrodes the Kn number must be adopted.

For step electrodes a calibre of a narrow part of an electrode l/d is of importance and it must be taken into consideration.Sometimes it is expedient to use three arguments also in plasmatrons with rear electrodes (as a rule, π_1 , π_5 , Kn are adopted). But for the heaters of this type three arguments are the limiting number since the number of the original dimensional variables is also equal to 3 (I , G , d).

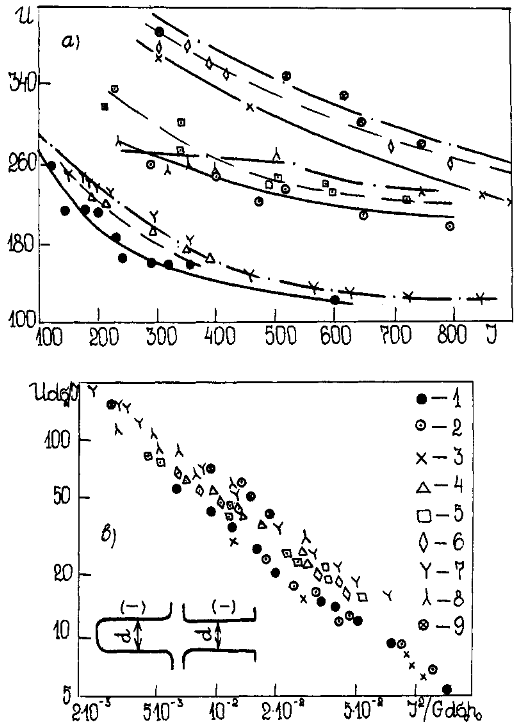


Fig.1. CVC of an electric arc nitrogen plasmatron with cylindrical electrodes: a) uncorrelated characteristics; b) correlated characteristic. 1, 2, 3, d = 1cm; 4, 5, 6, d = 2cm; 7, 8, 9, d = 4 cm. 1, 4, 7, G = 2g/s; 2, 5, 8, G = 4 g/s; 3 , 6 , 9 , G = 6 g/s.

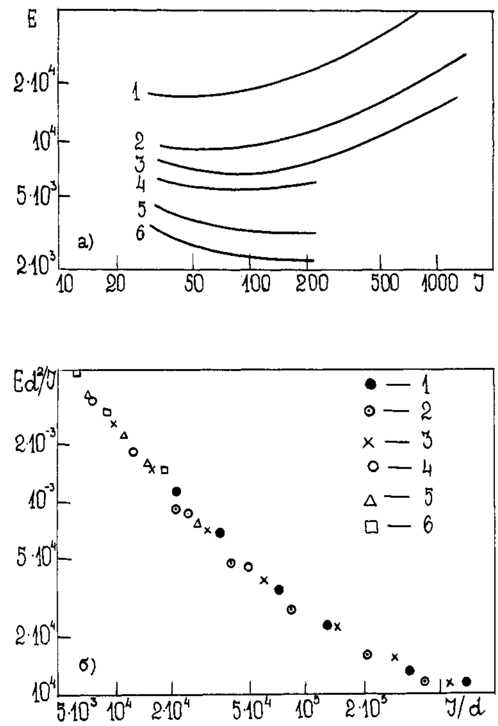


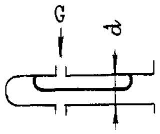
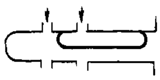
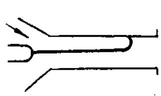
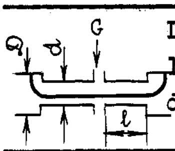
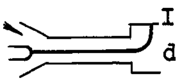
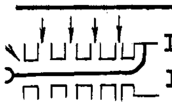
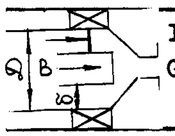
Fig.2. E-I characteristics of a water-stabilized arc. a) uncorrelated characteristics; b) correlated characteristic. Channel diameter: 1, 1.4mm; 2, 2.3; 3, 3.0; 4, 4.0; 5, 7.0; 6, 11.4 .

Generalizations of such kind lose much of their attractiveness. At pressures like the atmosphere one radiative transfer, as a rule, is of no importance and it has not been taken into consideration.

About relative significance of the criterion we may judge from the mean-square scatter of experimental points. Unfortunately , the correlation method makes it possible to define only the first predominant number. With respect to additional terms the efficiency of this method dramatically falls as far as their quantity increases. When the number of generalized arguments is equal to the number of initial independent variables, the method does not work at all and any set of criteria gives the same error. Besides, even with a choice of the first number a situation may take place that some insignificant argument will resemble by its structure a complex of significant arguments. Therefore the correlation method is necessary but not sufficient. In order to eliminate the "false" numbers, the correlation method should be used alongside the analysis of physical processes proceeding in an arc.

Table 1 lists CVC correlated data for some typical gas electric arc heaters. From the Table it is seen that in spite of various plasmatron designs employed by different authors , the correlated results are rather close. At the same time the effect of the test parameters ranges is observed.

TABLE 1. CVC correlation of different electric arc heaters in the form $F = c \prod_i A_i^{\alpha_i}$

Device diagram	Range of test parameters	Arguments A_1	A_2	A_3	C, α values	Error %	Ref. Nos.
	I =100–800; G =(2–6).10^{-3}; d = (10–40).10^{-3}; P =10^5;N_2	$\frac{Gd}{I^2}$	-	-	C =5.5.10^4 α_1=0.7	28	10
	I =40–180;P =10^5;d =0.01; G = 0.0033–0.0069; air	$\frac{Gd}{I^2}$	-	-	C = 6.8.10^4 α_1= 0.76	28 -	10 14
	I =30–200; G =(2.4–4.1).10^{-3} d =(6–35).10^{-3};P =10^5;air	$\frac{Gd}{I^2}$	$\frac{G}{d}$	Pd	C = 1.3.10^4 α_1=0.7; α_2=0.4; α_3=0.04	10	13
	I =40–200; G = (5–120).10^{-3} d =0.01–0.05; P =(1–10).10^5 air; a.c.	$\frac{Gd}{I^2}$	$\frac{G}{d}$	Pd	C =2160 α_1 =0.655 α_2 =0.345 α_3=0.2	-	16
	I =200–600;G =0.0075–0.0013 d = 0.01–0.03; H_2	$\frac{Gd}{I^2}$	Pd	-	C =9.6.10^3 α_1=0.7 α_2=0.36	-	17
	I = 200–700; G =0.02–0.13 P =(1–16).10^5;d=0.02–0.025; air	$\frac{Gd}{I^2}$	$\frac{G}{d}$	Pd	C =1290 α_1 =0.654 α_2 =0.205 α_3=0.25	11	15 18
	I = 220–1050; G =0.05–0.25 l =(25–100).10^{-3} d =(5–14).10^{-3}, air	$\frac{Gd}{I^2}$	$\frac{G}{d}$	$\frac{l}{d}$	C = 59 α_1 = 0.44 α_2 = 0.23 α_3 = 0.5	32	11
	I =200–1500; G < 0.19 d =35.10^{-3}; l =0.35; air	$\frac{Gd}{I^2}$	-	-	C =66 α_1=0.4	-	19
	I =200–1500; G < 0.19; l =21x15.10^{-3}; d =0.03;air	$\frac{Gd}{I^2}$	-	-	C =1.8.10^2 α_1=0.44	-	19
	I =125–900; B =0.085–0.29 G =(0–14).10^{-3} =(3–6).10^{-3}; D =0.04;air	$\frac{B}{I^3}$	$\frac{\delta}{D}$	-	C =1.25.10^4 α_1 =0.37 α_2 =0.38	11	20

[a]The formulae from (refs.16,17,19) have been transformed for the convenience of comparison.

[b] The complex Ud/I is used as a function in all cases.

GENERALIZATION OF ARC DISCHARGE CHARACTERISTICS IN DIMENSIONLESS CRITERIA

A governing temperature must be known a priori and must not depend on variation of other controllable parameters, i.e. current, flow rate and a kind of gas, geometric parameters. That is why the attempts to use the mean-mass temperature of a heated gas that depends on discharge conditions are no good. Besides, the mean-mass temperature is essentially lower than the discharge temperature.

Most of arc heaters employ weak-stabilized arcs oscillating in space. In such arcs temperature distribution non-uniformity over a column section is not essential and we may use a channel model with constant temperature. Moreover, a complicated dependence of plasma physical properties on temperature gives rise to some sufficiently narrow temperature ranges of unstable discharges. Variation of controllable parameters, in the first turn of current strength, weakly affects an arc temperature but exerts a greater influence on its dimensions.

Since the stable burning temperature of the unstable arc is specified mainly by physical properties, this offers possibilities to find scale values of the temperature. The method adopted in (ref.21) is most close to this approach. In this work an assumption is made that just at the inflection point of the curve $\sigma = f(h)$ the channel arc temperature sets up (Fig.3).

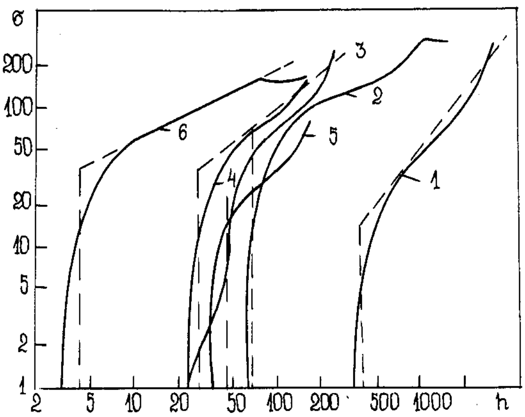


Fig. 3. Approximation of the dependence σ (h) by two segments of the power-law curves.
P= 10^{-1}MPa. I ,hydrogen; 2, helium; 3, nitrogen; 4, oxygen; 5, air; 6, argon.

A rise of the temperature above this point requires a drastic increase of energy contribution and slightly affects electric conductivity. The arc finds itself as if in front of a steep "mountain" to ascend which it must be stabilized.

Correlation of experimental CVC data for oxygen, nitrogen, helium , and argon in a heater with smooth cylindrical electrodes d = 2 cm with the use of the results produced by the above method yields the expression

$$Ud\sigma_0/I = 3.39\,(Gd\sigma_0 h_0/I^2)^{0.62};\quad \Delta = 30\%.$$

The further development of works concerned with generalization of arc characteristics has taken the way to account for the temperature dependence of plasma properties. In order to get a proper information about those sufficiently narrow temperature ranges in which weak-stabilized arcs are stable (refs.22, 23), the temperature dependence of plasma properties has been studied. For a narrow temperature range the power-law approximations of the form $\sigma/\sigma_0 = (T/T_0)^{n_\sigma}$ are quite acceptable. The exponents $n_\sigma(T)$; $n_h(T)$; $n_\lambda(T)$; $n_\rho(T)$; $n_\eta(T)$ $n_Q(T)$ in a temperature range up to $3 \cdot 10^4$K have been determined by using the expressions of the type: $n_\sigma = d\log\sigma/d\log T$

A "floating" temperature scale dependent on the discharge conditions is determined from the dominating criterion $\sigma^* h^* Gd/I^2 = 1$. This approach is based on dimensionless argument transformation into a function, if the known (T_0) value turns into the desired (T^*) . According to the Buckingham theorem the number of arguments reduces. Expressing the properties in terms of th temperature dependences the expression $(T^*/T_0)^{\gamma} = (Gd\sigma_0 h_0/I_2)^{-1}$ is determined where $\gamma = n_\sigma + n_h$ Correspondingly, for the generalized function we assume $Ud\sigma^*/I$. Using $\sigma^*(T)$,we may get $Ud\sigma_0/I = c(Gd\sigma_0 h_0/I^2)^{\delta}$ where $\delta = n_\sigma/(n_\sigma + n_h)$. Thus it appears that in the case of one dominating process the argument exponent depends only on plasma properties.

Therefore if the constant temperature scale T_0 and the character of the dominating process are known then the generalized CVC may be determined theoretically with an accuracry to the constant coefficient c . On the other side, assuming $\delta = \alpha$ we may determine T_0 by the experimental value of α .

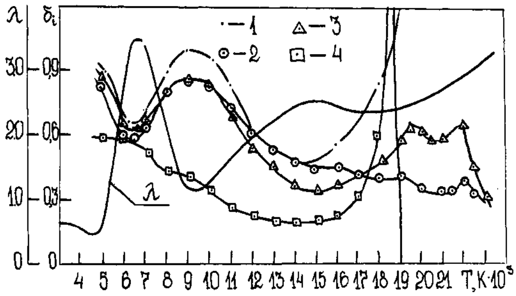


Fig. 4. Temperature dependence of the calculated exponents of dimensionless numbers for air arc CVC: 1, turbulence number; 2, heat conduction number; 3, blowing number; 4, radiative heat transfer number.

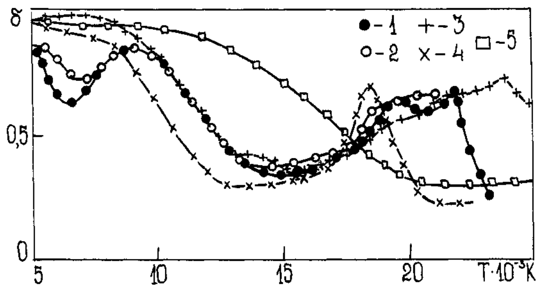


Fig. 5. Temperature dependence of of the calculated exponents of the blowing number of the generalized CVC: 1, air; 2, nitrogen; 3, hydrogen; 4, argon; 5, helium.

Fig.4 presents the dependences $\delta(T)$ for different dominating criteria of the air plasma, while Fig.5 presents the same dependences for the blowing numbers of different gases. Analysis of these figures allows some useful conclusions to be made.

It is a known fact that the unstabilized heavy-current arcs have flat CVC $U \approx$ const. If the dominating process is known then by using $\delta(T)$ one may determine T_o which in this case is practically equal to that of the arc. For the numbers containing I^2, $\delta = 0.5$. For instance, for the blown air arc T_o = 12300 K. Comparison to the experiment with a parallel-electrodes arc demonstrates a brilliant coincidence (T_o =12340 according to (ref.24)).

The present method of T_o determination is more grounded than the considered above using the data of (ref.21). Correspondingly, instead of the data given in Fig.3 we may recommend the data of Table 2 produced by the latter method.

TABLE 2. Scale values of temperature and properties of different gases for heavy-current arcs

Gas	T_o,K	$\sigma_o \cdot 10^{-2}$ $Ohm^{-1}.m^{-1}$	$h_o \cdot 10^{-6}$ J/kg	λ_o W/m.deg	$\rho_o \cdot 10^3$ kg/m^3
Nitrogen	12300	52,2	74,10	3,20	12,30
Argon	16700	35,3	7,33	0,72	43,00
Helium	17500	56,2	155,00	6,80	2,55
Hydrogen	12300	45,4	601,00	5,31	0,90
Air	12300	56.0	66.2	2.03	12.60

Comparison of the former and the new methods of T determination is made in (ref.23). Use of the new values has yielded a double increase of the accuracy of correlations.

In longitudinally-blown shunting heavy-current arcs $E \approx$ const and T_o will have the value indicated above. But shunting results in an increase of α that reduces T_o approximately by 1300 K. However, since the curves $\delta(T)$ of different gases coincide or have almost the same slope on working sections then ΔT_o values will be roughly equal and for weak-current arcs the "distorted" values may be used.

The working sections are the return slopes of $\delta(T)$ peaks since they correspond to the ascending sections of thermal conductivity peaks $\lambda(T)$ (Fig.4). Transition from one working section to another must be done by a jump. Amongst the working sections we may single out those with ascending CVC. For the criteria containing I^2 those are the segments of the curves $\delta(T)$ being below the values $\delta(T) = 0.5$.

The similarity of the plots $\delta(T)$ for different gases suggests an idea to use them for predicting CVC of non-tested gases. For this purpose it is necessary to build the plot $\delta(T)$ of a non-tested gas, to compare it with other similar plots and assume as the working plot the curve $\delta(T)$ for the known medium.

The above procedure for a single dominating process may be extended to several processes by using "weight" of the process æ. We assume $\sum_i \text{æ}_i = 1$. The value of T^* is found from the expression $\prod_i A_i^{\text{æ}_i} = 1$. The value of T_0 is determined at $\sum_i \varphi_i = 1$ where $\varphi_i = \gamma_i \text{æ}_i / \sum_i \gamma_i \text{æ}_i$. The weight may be calculated from the experimental exponents $\text{æ}_i = \alpha_i / \sum_i \alpha_i$ (ref.25).

Acknowledgements

The author is deeply grateful to his colleagues rendering him help in preparation of the report.

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