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Abstract. Generalization of average electric field strength for different discharge conditions in longitudinally blown arcs is considered. Experimental data for distinctive devices and different gases are used for physical modelling. Analysis has shown that heat transfer processes are responsible for I-E characteristic formation. Turbulent heat transfer was found to be the most effective for atmospheric pressure discharges while convection plays the main role in vacuum arcs. A generalized I-E characteristic is obtained.

Nomenclature

d - diameter of electrode; E - electric field strength; G - gas flow rate; h - enthalpy; I - current; l - length of discharge chamber; m, n - exponents; p - pressure; Π - similarity number; T, t - temperature; V - voltage; α - exponent; η, λ, ρ, σ - plasma properties: dynamic viscosity, thermoconductivity, density, and electroconductivity, respectively; subscript "0" denotes scale (characteristic) value of a property.

1. Introduction

At present, electric arc discharges are widely used for different purposes. Continuously broadening application of electric arc requires methods for arc characteristics determination. But the discharge is a very intricate phenomenon that impedes application of mathematical modelling. Theoretical simulation of the arc characteristic is possible only for discharges having simple geometric form and being rather stable. However, practical applications mostly deal with unstable blown arcs. Therefore, designers have to rely on experimental data. In such a situation, a method for electric arcs physical modelling based on similarity theory was proposed [1]. The method is mainly used for correlating experimental data on current-voltage (I-V) characteristics.

For longitudinally blown arcs, *I-E* (current-electric field strength) characteristics are important. They contain information about the major part of the arc column and are useful for estimation of the arc discharge chamber sizes. However, a very scanty information on *I-E* generalization is available in literature. An endeavor of *I-E* correlation for electric arcs y blown with different gases is made in this paper. Our own experiments together with data from literature [2-14] are used for the purpose. Field strength E was determined by measuring voltage between sections of cascade arcs. The average values are taken for correlation. These data are necessary for plasma torches design.

One of the most difficult problem for electric arc characteristics generalization follows from the distinctive plasma properties dependence on temperature for different gases.But such generalization is desirable in order to apply a universal relationship to uninvestigated working gases. To obtain universal *I-E* characteristic, we have used the method of scale plasma properties determination based on accounting for the properties dependence on temperature [15,16]. The method enables to correlate the integral arc characteristics.

Another topic of the research is the estimation of dominant mechanisms which control formation of arc characteristics. These processes are dependent on the discharge condition and on the working gas. The information is useful for any type of arc discharge including the cascade arc which is the most suitable for theoretical simulation. Regression analysis which is used for *I-E* generalization provides such a possibility. Knowing dominant processes allows to formulate appropriate mathematical model of a phenomenon. Moreover, unexpectable results can provide information for further development of the theory.

2. Methods of *I-E* characteristics correlation.

Generalized *I-E* characteristic of electric arcs are usually approximated by nondimensional power expressions. Dependent variable is taken in the form $Ed^2\sigma_0 / I$. The form of nondimensional arguments depend on the discharge conditions. Characteristics of such high-temperature phenomenon like electric arc discharge depend mainly on energy transfer processes. Therefore, the set of the numbers which were used for the selection included:

$\Pi_{conv} = Gd\,\sigma_0 h_0 / I^2$ – similarity number describing Joule energy dissipation transfer by convection

$\Pi_{cond} = \sigma_0 \lambda_0 T_0 d^2 / I^2$ – Joule energy transfer by conduction;

$\Pi_{rad} = \sigma_0 Q_{r0} d^4 / I^2$ – Joule energy transfer by radiation;

$\Pi_{turb} = \sigma_0 \rho_0 h_0^{1.5} d^3 / I^2$ – Joule energy transfer by thermal turbulence which average velocity is proportional to sq. root of enthalpy pulsation [17,18]

Account for gasdynamic processes was taken by "hot" and "cold" Reynolds numbers:

$\Pi_{re\text{-}hot} = G / \eta_{0hot} d$; $\Pi_{re\text{-}cold} = G / \eta_{0cold} d$;. The dynamic viscosity for $\Pi_{re\text{-}cold}$ was taken at t = 20°C and "hot" viscosity related to "scale" temperature T_0.

Dominant numbers were selected by step-wise 'forward'procedure [19,20].using multiple linear regression program from Windows. At zero step, every number from the set is tested separately. Comparative magnitude of regression determinant R^2 shows the relative importance of the process. The last step indicates the numbers which provide the best accuracy of regression. A computation program of the regression analysis gives the values of regression coefficients and statistical parameters.

"Scale" ("characteristic") values of plasma properties were estimated using method which takes account for the properties dependence on temperature. The temperature varies significantly over the arc column, but for every given regime it can be characterized by some average value T^*. Independent similarity numbers must include some constant characteristic values of the properties (they have subscripts "0"). But if one takes properties at temperature T^*, which depends on the arc discharge regime, the independent numbers convert into dependent ones. They must be constant when there are no independent arguments. Approximating plasma properties by power expressions in the vicinity of T_0 $\sigma^* / \sigma_0 = (T^* / T_0)^m$, $\lambda^* / \lambda_0 = (T^* / T_0)^n$, etc. and equating a number to 1.0, one may obtain T^* as function of initial variable parameters. For example, in the case of single dominant conductive mechanism $\sigma^* \lambda^* T^* d^2 / I^2 = \left(\sigma_0 \lambda_0 T_0 d^2 / I^2\right)\left(T^* / T_0\right)^{n+m+1} = 1$, and $T^* / T_0 = \left(\sigma_0 \lambda_0 T_0 d^2 / I^2\right)^{-1/(m+n+1)}$. Using this relation for dependent number gives the generalized *I-E* characteristic in the form $Ed^2 \sigma_0 / I = C\left(\sigma_0 \lambda_0 T_0 d^2 / I^2\right)^{\alpha}$; $\alpha = m/(m+n+1)$; $C = cons$. If theoretical value of exponent α is known as function of temperature it can be compared with its experimental magnitude. Thus, scale temperature T_0 can be found for some set of experimental data.

In the case of high current unstabilized arcs, one may take into consideration the degradation of the *I-V* ascendant branch into $V \approx cons$. For considered numbers it corresponds to $\alpha \approx 0.5$. So, scale temperature T_0 can be estimated theoretically. The values of scale properties estimated at $\alpha \approx 0.5$ are given in [16].

3. Results and discussion.

Experimental data for characteristics of arcs blown with air, argon, hydrogen and helium at atmospheric pressure are analysed in this paper. The parameters of discharges varied over ranges: $I = 7$ - 900 A; $d = 5$ - 30 mm; $G_{Air} = 1.2$ - 84 g/s; $G_{Ar} = 0.05$ - 16; $G_{H_2} = 0.58$ - 4.0; $G_{He} = 0.5$ - 4.0. Figure 1 shows dependent number $Ed^2\sigma_0 / I$ as function of different independent numbers. It is seen that the best correlation takes place when the turbulent number Π_{turb} is used as dominant one. A bend is noticeable at $\ln \Pi_{turb} \approx 9.0$. The other heat transfer numbers also provide the data correlation but the scattering is larger. Results of stepwise numbers selection are listed in table 1 which shows coefficient of determination R^2,ratio of regression variance to that of residuals F,and standart error SE.Zero step shows Π_{turb} to be dominant. But R^2 for Π_{cond} and Π_{conv} are also rather high. Nevertheless, the last step shows absence of Π_{conv} due to its high mutual correlation with Π_{turb}. .

Analysis of individual gases shows some difference in dominant processes. At atmospheric pressure,the first step shows turbulence to be dominant in air and hydrogen, radiation dominates in argon and conduction in helium But in all cases Π_{turb} is approximately as im-

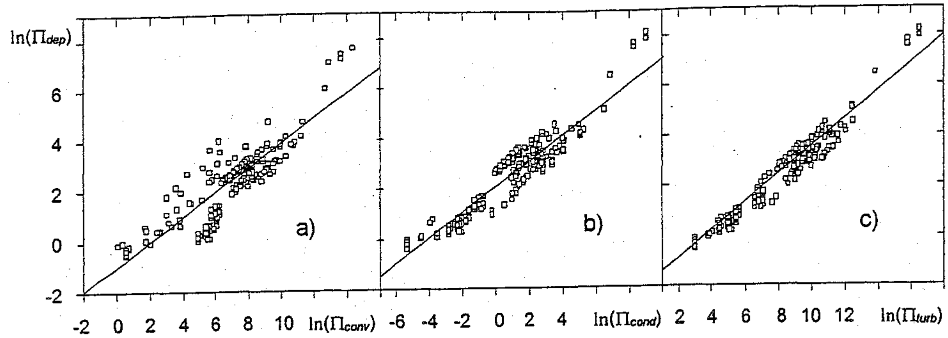

Fig. 1 Dependent number as functions of different arguments Π_{conv} *(a);* Π_{cond} *(b);* Π_{turb} *(c);*

portant as the first number and occupies the second position. Therefore, Π_{turb} is chosen as dominant for the common *I-E* characteristic.

Table 1 exhibits also the same data for ranges $\ln \Pi_{turb} < 9.0$ and $\ln \Pi_{turb} > 9.0$. From the viewpoint of numbers selection, the result is similar to the previous one: turbulence plays the main role, conduction and convection being also rather effective. The main benefit of the division results in reduction of the standart error from $SE = 0.36$ to $SE = 0.28$ and $SE = 0.25$, respectively.

Table 2 demonstrates summary for the three modes of correlation. It provides regression coefficients:standart β and raw B as well as students t-distribution with the corresponding degrees of freedom and probability level. The data conform to the following expression

$$\frac{Ed^2\sigma_0}{I} = 0.260\left(\frac{\sigma_0\rho_0 h_0^{1.5} d^3}{I^2}\right)^{0.424}\left(\frac{\sigma_0\lambda_0 T_0 d^2}{I^2}\right)^{0.144}\left(\frac{G}{\eta_{0\,hot} d}\right)^{0.049}.$$

It is remarkable that convection is excluded from the generalized I-E while in I-V characteristics for torches with "self–sustaining" length of arc it takes the dominant position. This result leads to conclusion that convective heat transfer is the dominant factor controlling electric break-down between the arc and electrode wall.

The residuals summary is shown in Table 3. A noticeable kurtosis is seen in the case of whole range and an appreciable skewness takes place at $\ln \Pi_{turb} < 9.0$. Fig.2 demonstrates Normal Probability Plot of Residuals for the whole range to be rather smooth. Though some deviation from the normality takes place, the generalization of I-E characteristics may be considered as successful in spite of different working gases and a number of distinctive designs being covered.

The cascade arc is the most suitable for theoretical simulation. But it is of great interest to analyse by regression methods the dominant mechanisms affecting I-E characteristic. Some our experimental data for discharges in argon and hydrogen at $p = (0.02 - 1.0) \times 105$ Pa, $I = 25 - 75$ A; $G_{Ar} = (0.03 - 0.3)$ g/s; $G_{H2} = (0.005 \div 0.013)$ g/s; $d = 4$ mm, $l = 60$ mm (for argon), $l = 30$ mm (for hydrogen) were used for the analysis.

Table 4 presents the results of sequential numbers selection for *I-E* in argon, and hydrogen. It is seen that vacuum arcs are more permeable for gas flow than ones at atmospheric pressure, and convection becomes the dominant mechanism. The residuals summary for individual gases show rather good normality. It is seen in Fig. 3 presenting the Normal Probability Plot of Residuals for argon.

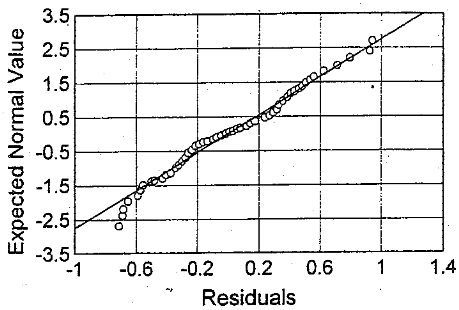

Fig. 2 Normal Probability Plot of Residuals (Discharge at atmospheric pressure whole range).

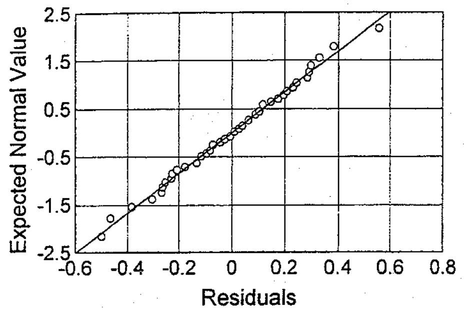

Fig. 3 Normal probability Plot of Residuals (Discharge in argon at subatmospheric pressure).

Table 1. Sequential selection of variables for discharges at atmospheric pressure.

Regress. parameter	Step	Variables					
		Π_{conv}	Π_{cond}	Π_{turb}	Π_{rad}	$\Pi_{re\text{-}hot}$	$\Pi_{re\text{-}cold}$
whole range							
R^2	zero	.740292	.880668	.943058	.362148	.056320	.045811
F	zero	536	1387	3114	107	11	9
R^2, SE	last	R^2 = . 94857031, SE =.36005					
F	last	–	14	3412	–	6	–
range ln(Π_{turb}) < 9							
R^2	zero	.620561	.796458	.923011	.296733	.016824	.013402
F	zero	192	462	1415	50	2	1.6
R^2, SE	last	R^2 = . 94491143, SE = .27987					
F	last	–	17	1927	8	20	–
range ln(Π_{turb}) > 9							
R^2	zero	.547408	.793088	.89580	.07735	.023338	.044108
F	zero	82	261	585	6	2	3
R^2, SE	last	R^2 = . 96049318, SE = .24746					
F	last	–	51	1474	22	33	–

Table 2. Regression summary for dependent variable

	β	St. Err. of β	B	St. Err. of B	t(186)	p-level
Whole range						
R = .97394574 R^2 = .94857031 Adjusted R^2 = .94774080 F(3,186) =1143.5 p < 0.0000 Std.Error of estimate: .36005						
Intercpt			-1.34745	.220687	-6.10572	.000000
TURB	.740752	.055208	.42386	.031590	13.41754	.000000
COND	.256645	.057879	.14396	.032466	4.43417	.000016
RE_HOT	.049000	.019412	.04906	.019436	2.52419	.012433
range $\ln(\Pi_{turb}) < 9$						
R = .97206555 R^2= .94491143 Adjusted R^2= .94299531 F(4,115)=493.14 p<0.0000 Std.Error of estimate: .27987						
Intercpt			-3.25167	.317192	-10.2514	.000000
TURB	1.309231	.084882	.75849	.049175	15.4242	.000000
RAD	.332712	.051734	.06505	.010114	6.4312	.000000
COND	-.536672	.110009	-.28954	.059351	-4.8784	.000003
RE_HOT	.117197	.025679	.09616	.021069	4.5639	.000013
range $\ln(\Pi_{turb}) > 9$						
R = .98004754 R^2 = .96049318 Adjusted R^2 = .95806199 F(4,65)=395.07 p<.00000 Std.Error of estimate: .24746						
Intercpt			-1.10124	.305907	-3.59991	.000616
TURB	.200399	.078659	.14298	.056121	2.54770	.013217
COND	.989986	.101239	.61354	.062742	9.77871	.000000
RAD	-.290085	.046953	-.07390	.011962	-6.17826	.000000
RE_HOT	.197291	.034110	.13825	.023902	5.78388	.000000

Table 3. Residual summary for discharges at atmospheric pressure

	Variance	Std.Dev.	Standard Error	Skewness	Std.Err. Skewness	Kurtosis	Std.Err. Kurtosis
Whole range							
RESIDUAL	.135443	.368025	.026699	-.136341	.176323	-.525048	.350872
range $\ln(\Pi_{turb}) < 9$							
RESIDUAL	.075694	.275125	.025115	-.894625	.220879	.327533	.438331
range $\ln(\Pi_{turb}) > 9$							
RESIDUAL	.057686	.240180	.028707	.218815	.286750	-.254199	.566265

Table 4. Sequential analysis of variables for discharges at subatmospheric pressure.

Regress. parameter	Step	Variables					
		Π_{conv}	Π_{cond}	Π_{turb}	Π_{rad}	$\Pi_{re\text{-}hot}$	$\Pi_{re\text{-}cold}$
Ar							
R^2	zero	.521622	.130411	.141441	.199546	.297641	.297641
F	zero	46	6	7	8	18	18
R^2, SE	last	R^2 =.521622, SE =.23421					
F	last	2.51208	–	–	–	–	–
H_2							
R^2	zero	.933914	.875782	.875782	.875782	.919201	.919201
F	zero	287	134	134	134	216	216
R^2, SE	last	R^2 =.93791372, SE =.08160					
F	last	287	–	–	–	–	–

In contrast to atmospheric pressure, the common *I-E* in vacuum differs significantly from ones for individual gases. It shows rather high effect of Π_{turb} , Π_{conv} and Π_{rad} . This phenomenon is unintelligible yet and needs for special investigation.

4. Conclusions

The generalized *I-E* characteristic is obtained for longitudinally blown arcs. The characteristic can be used for the designing of plasma torches operating with different gases. Analysis of the relative role of individual processes in *I-E* characteristic formation has shown heat transfer to be the most effective. Energy transfer by thermal turbulence has turned to be one of the most important for arc discharges at atmospheric pressure; but in vacuum arcs, the main role belongs to convective mechanism. Comparison with generalized *I-V* characteristics derived for arcs with "self-sustaining" length shows appreciable effect of heat convection on electric break-down between the arc column and electrode wall.

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References

1. Yas'ko O.I. 1969. Brit. 1969. J. Appl. Phys. (J. Phys. D.). Ser. 2. Vol. 2. 733-751.
2. Pustogarov A.V. 1966. Thermophys. High Temper. (THT) Vol.4, №2. 173-176. (russian).
3. Chesnokov N.A., G.P.Stelmah, A.S.Sahiev, 1966. THT, Vol.4. №2. 274-278. (russian).
4. Voronin B.D. B.V. Zolotov,M.Ya. Smelyansky, A.M. TzirlinV.P.Tzishevsky. 1963. "Electrothermy", №5. 13-17. (russian).
5. Bertinov A.I. D.A.But,P.V.Vasyukevich,V.V.Popov,V.D.Tzarkov. 1968. THT. Vol.6, №3. 537-539. (russian).
6. Dautov G.Yu.,Yu.S.Dudnikov,M.F.Zhukov,M.I.Sazonov. 1965. Appl. Mech. and Tech. Phys. (AMTP). №5, 132-135. (russian).
7. Anshakov A.S. M.F.Zhukov,M.I.Sazonov,A.N.Timoshevsky. 1970. Sib. Branch of USSR Acad. of Sci. News. issue 2, №8. 3-11 (russian).
8. Dautov G.Yu. and M.I.Sazonov, 1967. AMTP. №4. 127-131 (russian).
9. Asinovsky E.I. and V.I.Shabashov, 1969. THT. Vol. 7, №2, 217-232 (russian).
10. Asinovsky E.I.,E.V.Drokhanova,A.V.Kirillin,A.N.Lagarkov. 1967. THT. Vol.5. №5, 739-750 (russian)
11. Voronin B.D., A.M.Tsirlin, M.Ya. Smelyansky. 1966. Sib. Branch of USSR Acad. of Sci. News. issue 3, №10. 57-65 (russian).
12. Asinovsky E.I., V.L.Nizovsky and V.I.Shabashov 1973. In "Plasma-jets generators and high-current arcs". "Nauka". Leningrad. 44-66 (russian)
13. Dautov G.Yu. and M.I.Sazonov. 1969. In "Generators of Low-Temperature Plasma". "Energia", Moscow. 200-208 (russian).
14. Kolonina L.I. and V.Ya.Smolyakov. 1969. In "Generators of Low-Temperature plasma". "Energia". Moscow. 209-218.
15. Yas'ko O.I. 1990. Pure & Appl. Chem. Vol. 62, №9. 1817-1824.
16. Yas'ko O.I.,A.Marotta.T.V.Laktyushina and L.O.M.da Silva. 1995. ISPC-12, Aug. 21-25. Minneapolis. USA. 1909-1914
17. Laktyushina T.V.,G.P.Lizunkov,V.D.Shimanovich and O.I.Yas'ko.1993.High Temp .Chem.Processes **2**.167-178
18. Podenok L.P.,V.D.Shimanovich,L.I.Sharakhovsky and O.I.Yas'ko.1994.High Temp. Chem. Processes **3**.409-418
19. Mayer R.H. 1989. Classical and Modern Regression with Applications. Boston: PWS-KENT.
20. Draper N.R. and H.Smith. 1981. Applied Regression Analysis. 2 nd ed. New York: John Wiley & Sons.