EFFECT OF GAS FLOW RATE AND ELECTRODES DIAMETER VARIATION IN THE SIMILARITY OF PLASMA TORCHES CHARACTERISTICS FOR DIFFERENT METHODS OF EXPERIMENTAL DATA APPROXIMATION

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ABSTRACT

Two methods of plasmatron current-voltage characteristics (CVC) approximation (empiric power expressions and generalized power relationships) for two types of d.c. vortex plasma torches (one with rod cathode and tube anode and another with both tube electrodes) are considered. Generalized relationships are shown to provide better CVC similarity.

INTRODUCTION

Mathematical modeling of electric arc discharges is impeded by phenomena complexity, arc column intricate and unstable form, and by turbulence of ambient blowing gas flow. Therefore, investigators have to apply physical modeling using experimental data. The problem of suitable approximation expressions arises in latter case. Application of conventional empirical expressions, for instance a power relationship of the form $U = cI^{\alpha}G^{\beta}d^{\gamma}$, gives the possibility to elucidate the relative role of different parameters in CVC formation. However, such approximation doesn't reveal energy transfer conditions and involves many variables.

Approximation of real relationships by generalized expressions with complex similarity numbers enables accounting of arc characteristics dependence on different heat transfer processes and provides the scope for the reduction of arguments number without initial variables restriction. Generalized expressions allow also to detect the relative role of individual energy transfer mechanisms in arc characteristics formation. But the main merit of generalization is the characteristic similarity at numbers constant value regardless the initial parameters variation. Unfortunately, the complete arc characteristics similarity is impossible to attain due to the variety of phenomena. Therefore investigator has to use an approximate modeling applying incomplete similarity which calls for selection of dominant processes.

To optimize the choice of the dominant variables for given experimental conditions, the dispersion analysis may be used [1]. The discrepancy caused by any parameter may be estimated by Fisher variances ratio. The effect of an additional parameter is negligible when the ratio of extra regression and total scattering variances occurs to be less than corresponding table value with a suitable probability.

The lamination, brought about by any individual variable included into complex similarity number, may be evaluated by Fisher ratio of lamination and random scattering variances. The latter variance can be determined as the ratio of squared deviations sum for all individual values of the considered parameter and the corresponding degree of freedom. The sums of squared deviations and degrees of freedom for lamination are calculated as the differences between total and random magnitudes. The last method may also be used for estimation of lamination Fisher ratio in the case of approximation by empiric formulae.

We have compared CVC power approximations by empiric and generalized expressions for two types of vortex plasmatrons. Different regression parameters and Fisher ratios were considered.

EXPERIMENTAL

D.c. plasmatrons with longitudinally-vortex blown arc (vortex plasmatrons) are mostly used for different purposes. Low-power vortex plasmatrons usually have a rod cathode and a tube anode, while more powerfull ones are equipped with two tube electrodes. Therefore, both these types of plasmatrons have been investigated in this work. Rod (zirconium) cathode had 9.2 mm internal diameter anode and operated with air at power 15-40 kW. To analyze gas flow-rate effect on CVC lamination, its magnitude was fixed at eight levels: 1.26, 1.64, 2.05, 2.45, 2.94, 3.33, 3.83 and 4.27 g/s; and current varied from 38 to 146 A.

More powerfull plasmatron incorporated two tube copper electrodes of equal internal diameters aligned in series along the axis. The polarity of electrodes were analogous to the rod cathode plasmatron: the back closed electrode served as cathode, and the front open tube was used as anode. Working gas was supplied through a vortex inlet chamber made of insulated material and disposed between the electrodes. The electrodes length was adjusted to the arc extent at the maximum gas flow rate: arc roots had to rotate around tube walls without sticking to the end wall of cathode and blowing off from anode. Three electrode diameters were used in experiments - 10, 20 and 40 mm. Plasmatron operated with nitrogen at three flow-rate values (2, 4 and 6 g/s) with each diameter. Current varied from 40 to 900 A that corresponded to power range 30-220 kW.

RESULTS AND DISCUSSION

Comparison of empiric and generalized CVC approximations were done for each gas flow-rate in the case of rod-cathode plasmatron. Because of constant anode diameter value, current-voltage characteristics for every constant gas flow-rate were taken in the form $U = cI^{\alpha}$ and $U/I = c(1/I^2)^{\alpha}$ for empiric and generalized expressions, respectively. Formulae $U = cI^{\alpha}G^{\beta}$ and $U/I = c(G/I^2)^{\alpha}$ were used for whole data file. The obtained regression parameters are listed in tables 1 and 2, where numerators and denominators present data for empiric and generalized approximations, respectively.

The tables show that any particular gas flow rate approximations by generalized power expressions are better than by empiric formulae. While r.m.s. deviations remain at the same level, enhancement of exponents in the cases of generalized expressions entails improvement of correlation coefficients, Student quantiles and regression Fisher ratios. For whole data file, the reduction of arguments number from two to one deteriorates regression parameters of generalized expression in comparison with empiric formula.

Since plasmatron with two tubes electrodes was investigated at three different diameters, the approximations for individual gas flow-rates were taken in forms $U = cI^\alpha d^\beta$ and $(Ud/I) = c(Gd/I^2)^\alpha$. Table 3 illustrates the results of regression analysis. Here again, numerator shows regression parameters of empiric formula and denominator represents generalized case.

As can be seen from table 3, correlation coefficients, Student quantiles and Fisher ratios are better for the case of generalized expression in comparison with empiric formulae in spite of arguments number reduction. But r.m.s. deviation depends mostly on variances number increasing with their reduction.

The same result was obtained for whole data file when expressions $U = cI^\alpha d^\beta G^\gamma$ and $(Ud/I) = c(Gd/I^2)^\alpha$ were compared. The arguments number reduction from three to one resulted in r.m.s. deviation rise from 2.86×10^{-2} to 8.3×10^{-2} but all other regression parameters appeared to be better for generalized expression (for example, regression Fisher ratio amounted to 386 and 1482, respectively).

Estimation of CVC lamination caused by gas flow-rate for the compared approximation methods and two plasmatron types is presented in table 4. Variants 1 and 2 correspond to rod cathode plasmatron for $U = cI^2$ and $(U/I) = c(G/I^2)^\alpha$ approximations, respectively. For plasmatron with tube electrodes, cases 3 and 4 relate to $U = cI^\alpha d^\beta$ and $(Ud/I) = c(Gd/I^2)^\alpha$ formulae. The vertically disposed numbers represent: sum of squared deviations SS, degrees of freedom, N and variance S^2.

It is seen from table 4 that gas flow-rate exerts appreciable CVC discrepancy. Lamination Fisher ratios for empiric approximations (cases 1 and 3) considerably exceed the table magnitudes. However, generalized expressions diminish the lamination. The reduction is especially significant for plasmatron with two tube electrodes - the lamination Fisher ratio appears to be smaller than table values. It means that in such plasmatrons gas flow-rate influences predominantly the convection heat transfer mechanism. But CVC generalization by the only convection similarity number is not so good for the case of rod-cathode plasmatron. Numbers, which represent also some other heat transfer mechanisms, have to be used for CVC generalization of this plasmatron.

The same method of CVC lamination analysis may be used for elucidation of electrodes diameter effect for tube-electrodes plasmatron. Table 5 exhibits regression parameters of individual diameters CVC, approximated with empiric formula $U = cI^\alpha G^\gamma$ (numerator) and with generalized expression $(Ud/I) = c(Gd/I^2)^\alpha$ (denominator).

The same CVC behavior is seen for individual electrode diameters as for particular gas flow-rates. Compared to empiric formulae, the generalization improves all regression parameters at approximately equal r.m.s. deviations.

Table 6 demonstrates CVC separation caused by the change of electrodes diameter. Variant 4 relates to generalized expression $(Ud/I) = c(Gd/I^2)^\alpha$, and case 5 corresponds to empiric formula $U = cI^\alpha G^\beta$. Meaning of vertically disposed numbers are the same as in table 4.

Table 6 shows that effect of electrodes diameter variation on CVC is rather small. The lamination Fisher ratio for empiric formula approximation only slightly exceeds the table values (variant 5). However, application of generalized expression results in perceptible discrepancy rise due to diameter change. Hence, there must be another, affected by electrode diameter substantial process, except convective heat transfer. A few of essential processes depend on electrode diameter, but there is yet lack of proper experimental data to reveal their relative role in the considered case. Most investigators consider Reynolds number as preferable one.

CONCLUSIONS

Comparison of two CVC approximation methods shows predominance of generalized expressions over simple empiric formulae. They demonstrate better regression parameters even if the arguments number is less than in empiric relations. At the equal variables number, the r.m.s. scatters are also approximately equal. But the main merit of generalized expressions is CVC similarity at individual variables variation.

NOMENCLATURE

c - constant; d - electrode diameter; F - Fisher variances ratio; G gas flow-rate; I - electric current; U - voltage; α, β, γ - exponents.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. A.A.B. do Prado, Mr. J.B. Pinheiro and Mr. M.G. Inácio for their technical assistance to this work. We acknowledge the financial support of CNPq, FAPESP and FINEP of Brazil.

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Table .1: Regression parameters for rod-cathode plasmatron CVC approximations at individual gas flow-rates

Parameter	Gas flow rate, G, g/s							
	1.27	1.64	2.05	2.45	2.94	2.33	3.83	4.27
C×1 Factor C×10^2	617 366	708 364	724 314	676 273	612 218	813 249	813 232	871 200
Exponent α	-0.23 0.61	-0.23 0.61	-0.22 0.61	-0.19 0.60	-0.18 0.59	-0.21 0.60	-0.20 0.60	-0.20 0.60
R.m.s deviation, $\sigma \times 10^4$	56 56	48 48	49 49	31 31	36 36	65 65	58 58	63 63
Correlation coefficient, K×10^3	-978 999	-985 999	-984 999	-991 999	-989 999	-977 999	-983 999	-984 999
Student quantile, t	27 148	33 180	32 182	44 283	40 259	27 157	31 187	32 188
Fisher ratio for regression, $F_{reg.}$	7.38 21953	1114 32564	1046 33165	1958 80231	1579 66956	709 24577	981 35031	1018 35382

Table .2: Regression parameters for rod-cathode plasmatron CVC approximations at whole gas flow-rates

Fator C	Exponent α	Exponent β	r.ms. deviation $\sigma \times 10^4$	Correlation coefficients K×10^3				Student quantiles		Fisher ratio for regression $F_{reg.}$
				U-I	U-G	I-G	$\frac{U}{I} - \frac{G}{I^2}$	t_α	t_β	
5495	-0.20	0.34	86	-607	918	262		-54	111	9829
2360	0.52		345				984	93		8585

Table .3: Regression parameters in different methods of CVC approximation for d.c. arc vortex plasmatron with two tube electrodes operating with nytrogen

Gas flow rate G, g/s	Fator C	Exponent		r.m.s. deviation $\sigma \times 10^4$	Correlation coefficients, K			Student quantiles, t		Fisher ratio for regression $F_{reg.}$
		α	β		$F - A_{r1}$	$F - A_{r2}$	$A_{r1} - A_{r2}$	$t\alpha$	t_β	
2	1.71×10^3 3.24×10^5	-0.41 0.80	0.08	302 938	-0.93 0.98	0.19	-0.30	-17 24	4	153 579
4	1.66×10^3 2.44×10^5	-0.82 0.78	0.05	248 760	-0.89 0.98	0.32	-0.21	- 8 21	2	43 432
6	6.35×10^3 1.04×10^6	-0.42 0.85	0.10	203 765	-0.93 0.98	0.45	-0.17	-14 21	5	131 428

Table .4: Analysis of CVC lamination caused by gas flow-rate variation

Appro-xi-ma-tion va-riant	Total deviation $SS \times 10^3$ N $S^2 \times 10^5$	Random scattering $SS \times 10^3$ N $S^2 \times 10^5$	Laminati-on $SS \times 10^3$ N $S^2 \times 10^5$	Laminati-on Fisher ratio F_{lam}	Table values of Fisher ratio F_{tabl}		Regres-sion Fisher ratio F_{reg}	$\frac{F_{lam}}{F_{reg}} \times 100\%$
					5%	1%		
1	938 286 328	7.36 272 2.71	930 14 6646	2456	1.73	2.15	167	1471
2	340 286 119	6.31 272 2.32	334 14 2383	1027	1.73	2.15	8585	12
3	941 66 1426	42 60 69	899 6 14980	215	2.25	3.12	2.18	9900
4	461 67 688	449 63 714	12 4 283	0.396	2.51	3.62	1482	0.03

Table .5: CVC regression parameters for tube electrodes plasmatron

Dia-metre cm	Fator C	Exponent		r.m.s. devia-tion $\sigma \times 10^4$	Correlation coefficients, k			Student quantiles, t		Fisher ratio for regres-sion F_{reg}
		α	γ		$F - A_{r1}$	$F - A_{r2}$	$A_{r1} - A_{r2}$	t_α	t_β	
1	1.73×10^5 4.75×10^4	-0.43 0.72	0.72	258 251	-0.01 0.99	0.65	0.67	-14 52	19	190 2702
2	6.08×10^4 2.04×10^4	-0.33 0.66	0.63	193 204	-0.11 0.99	0.80	0.48	-16 60	27	360 3550
4	1.22×10 0.91×10	-0.39 0.70	0.68	324 317	-0.20 0.99	0.72	0.50	-12 45	18	169 2009

Table .6: Analysis of CVC lamination caused by electrodes diameter change

Model	Total deviation $SS \times 10^3$ N $S^2 \times 10^5$	Random scatter $SS \times 10^3$ N $S^2 \times 10^5$	Laminati-on $SS \times 10^3$ N $S^2 \times 10^5$	Laminati-on Fisher ratio F_{lam}	Table values of Fisher ratio F_{tabl}		Regres-sion Fisher ratio F_{reg}	$\frac{F_{lam}}{F_{reg}} \times 100\%$
					5%	1%		
4	461 67 688	428 63 68	418 4 10450	154	2.51	3.63	1482	10
5	76.5 66 116	41.4 60 69	35.1 6 586	8.5	2.25	3.12	399	2.1