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SIMILARITY OF PLASMATRON CHARACTERISTICS FOR LONGITUDINAL VORTEX FLOW AROUND THE ARC WITH VARIATIONS IN THE GAS FLOW RATE

T. V. Laktyushina,[a] A. Marotta, [b] and
A. I. Yas'ko[a]

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The volt-ampere characteristics (VAC) of an electric arc are correlated with longitudinal vortex air and nitrogen flows in plasmatrons with a rod-like cathode and two tubular electrodes. Two types of exponent approximations are used: a simple empirical formula and a relationship between generalized variables. It is shown by methods of regression analysis that the use of generalized variables provides similarity of the VAC upon variations in the gas-flow rate.

Mathematical modeling of blown-off electric arcs presents difficulties due to the complexity of the variety of processes that take place in the discharge, and as a result of the instability of the arc discharge and flow turbulization. Therefore attention is frequently drawn to physical modeling based on experimental data. In this case the problem arises of the choice of expressions for approximation of discharge characteristics. Both conventional empirical formulas and dimensionless relationships between similarity numbers are used.

Empirical expressions, e.g., in the form of a power approximation of the dependence of the voltage across the arc on the geometrical and regime parameters $U = AI^{\alpha}G^{\beta}d^{\gamma}$, provide an opportunity to present clealy the relative roles of different parameters in the formation of the VAC of the discharge. However, such an approximation does not reflect the effect of the conditions of energy and mass exchange and involves the use of a great number of independent variables.

Approximation of experimental data in terms of generalized variables makes it possible to take into account the dependence on the character of heat transfer in the arc column and to reduce, for a certain dominating type of heat exchange for which the other types can be neglected, the number of independent variables to one without narrowing the range of variation of all original variables. In the case of the simultaneous effect of several types of heat transfer, one can take into account the relative roles of the separate types of the energy transfer. However, the main advantage of generalized variables is similarity of characteristics upon variations in separate dimensional variables with conservation of the values of dimensionless similarity numbers.

Unfortunately, total similarity of the characteristics of electric discharges cannot be attained, due the great variety of processes that take place in arcs and their complex interplay. In this case, one must resort to approximate modeling in which the incomplete similarity is possible upon variation of certain dimensional parameters. Therefore estimates of similarity completeness should be carried out in physical modeling in order to provide a choice of similarity numbers that reflect the most important processes.

The correctness of the choice of the necessary number of the most important similarity similitude numbers can be controlled by the methods of regression analysis [1]. Deviation from similarity for one of the parameters is characterized by variance of the stratification of the generalized characteristics with variation of the parameter. The deviation does not fall outside the random scatter if the experimental value of Fisher's ratio of the deviation variance to the variance of the random scatter does not exceed the theoretical value with a certain probability. The distinctive features of high-temperature phenomena are characterized mainly by heat transfer processes. Therefore, the question of the possibility ensuring similarity when using numbers that reflect only heat transfer processes arises

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TABLE 1. Regression Parameters of the VAC of a Linear Plasmatron with Rod-Like Cathode with the Air Flow Around the Arc

Gas flow rate, G, g/sec	Mean-square deviation from the regression, Δ	Correlation coefficient	Student's quantile	Fisher's regression criterion, F_r
		$U - I$	t	
4.27	0.0063	−0.984	−31.9	1018
3.83	0.0058	−0.983	−31.3	981
3.33	0.0065	−0.977	−26.6	709
2.94	0.0036	−0.989	−39.7	1579
2.45	0.0031	−0.991	−44.2	1958
2.05	0.0049	−0.984	−32.3	1046
1.64	0.0048	−0.985	−33.4	1114
1.27	0.0056	−0.978	−27.2	738
For all G	0.0573	−0.607	−12.9	167

TABLE 2. Similitude Analysis of Plasmatron Characteristics with Rod-Like Cathode upon Variations in the Gas Flow Rate (air, longitudinal vortex flow around the arc)

Regression parameters	Values of parameters for different approximation methods	
	$U = AI^{\alpha}$	$U/I = A(G/I^2)^{\alpha}$
Sum of squared residuals for correlation over all gas flow rates	0.9377537	0.3399134
Number of degrees of freedom for sum total of residuals	286	286
Sum total of squared residuals for correlation over separate flow rates	$0.7358931 \cdot 10^{-2}$	$0.6312549 \cdot 10^{-2}$
Total number of degrees of freedom for correlation over separate flow rates	272	272
Dispersion for correlation over separate flow rates	$2.705 \cdot 10^{-5}$	$2.32 \cdot 10^{-5}$
Sum of squared residuals due to stratification of VAC over flow rates	0.9303948	0.3336009
Number of degrees of freedom of VAC stratification	14	14
Variation of residuals due to VAC stratification	$0.6645677 \cdot 10^{-1}$	$0.2382863 \cdot 10^{-1}$
Fisher's dissimilarity criterion over flow rates, F_d	2456	1027
Tabulated value of Fisher's criterion (5%/1%)	1.73/2.15	1.73/2.15
Fisher's regression criterion, F_r	167	8585
Ratio of criteria F_d/F_r, %	1471	12

in modeling of arc discharges. For a certain working medium with a constant composition and geometrical dimensions of the discharge chamber, similarity is characterized by scatter levels with variations in the gas flow.

Dc electric-arc plasmatrons with longitudinal vortex flow of the gas being heated around the arc are frequently used in various applications. Rod-like cathodes are freqeuntly used in plasmatrons of small and average

TABLE 3. Regression Parameters for the VAC of Linear Plasmatron with Tubular Electrodes of Equal Diameters upon Variations in the Gas Flow Rate (technical nitrogen flow around the arc)

Gas flow rate G, g/sec	Form of the approximation	Mean-square deviation of the regression Δ	Correlation coefficients				Student's quantiles		Fisher's regression F_r
			$U-I$	$U-d$	$I-d$	$U_d/I - Gd/I^2$	t_α	t_γ	
2	$U = AI^\alpha d^\gamma$	0,301861	−0,934	0,189	−0,300	–	−17,1	3,95	153
4	$U = AI^\alpha d^\gamma$	0,0247832	−0,889	0,370	−0,207	–	−8,47	1,94	43
6	$U = AI^\alpha d^\gamma$	0,0203337	−0,925	0,453	−0,168	–	−14,3	5,03	131
Σ	$U = AI^\alpha d^\gamma$	0,1194022	−0,137	0,214	−0,46	–	−1,07	1,74	2,18
2	$Ud/I = A(Gd/I^2)^\alpha$	0,0937717	–	–	–	0,977	24,1	–	579
4	$Ud/I = A(Gd/I^2)^\alpha$	0,0759651	–	–	–	0,979	20,8	–	432
6	$Ud/I = A(Gd/I^2)^\alpha$	0,0764961	–	–	–	0,982	20,7	–	428
Σ	$Ud/I = A(Gd/I^2)^\alpha$	0,0829307	–	–	–	0,978	38,5	–	148,2

TABLE 4. Similarity Analysis of Characteristics of Plasmatron with Tubular Electrodes of Equal Diameters upon Variations in the Gas Flow Rate

Regression parameters	Values of parameters for different approximation methods	
	$U = AI^\alpha d^\gamma$	$Ud/I = A(Gd/I^2)^\alpha$
Sum of squared residuals for correlation over all gas flow rates	0.9409552	0.4607925
Number of degrees of freedom for sum total of residuals	66	67
Sum total of squared residuals for correlation over separate flow rates	0.0418601	0.4494774
Total number of degrees of freedom for correlation over separate flow rates	60	63
Total dispersion for correlation over separate flow rates	$6.977\cdot10^{-4}$	$7.135\cdot10^{-3}$
Sum of squared residuals due to stratification of VAC over gas flow rates	0.8990951	0.0131510
Number of degrees of freedom of VAC stratification	6	4
Variation of residuals due to VAC stratification	$1.498\cdot10^{-1}$	$2.828\cdot10^{-3}$
Fisher's dissimilarity criterion over gas flow rates, F_d	215	0.396
Tabulated value of Fisher's criterion (5%/1%)	2.25/3.12	2.51/3.62
Fisher's regression criterion, F_r	2.18	1482
Ratio of criteria F_d/F_r, %	9900	0.03%

power, whereas tubular cathodes are used in more-powerful installations. Therefore, in the present work we analyze the characteristics of plasmatrons of both types. A plasmatron with a rod-like zirconium cathode was operated in air at powers of from 15 to 40 kW. The current was varied from 38 to 146 A, and the air flow from 1.26 to 4.27 g/sec. The inner diameter of the tubular copper anode was equal to 9.5 mm. In order to analyze the effect of the gas flow on the stratification of the characteristics, they were taken at the following flow rates: 1.27, 1.64, 2.05, 2.45, 2.94, 3.33, 3.83, and 4.27 g/sec.

Higher powers were reached in a plasmatron with tubular electrodes. The plasmatron consisted of two electrodes that had equal inner diameters and were placed coaxially. The electrodes were fabricated from copper and were cooled from the outside by flowing water. The polarity of the electrodes was the same as in the case of the rod-like cathode, i.e., the inner closed tubular electrode was the cathode and the outer flow-through electrode played the role of the anode. The gas was fed into the gap between the electrodes via a vortex chamber fabricated from an insulating material. The length of the electrodes was such that at the maximum gas flow rate the arc anode spot would not be blown out to the face of the outer electrode, and the cathode spot would not be blown off to the inner face wall of the rear electrode.

Installations with three different inner diameters, 10, 20, and 40 mm, were used in the experiments. For each of the diameter values three different gas flow rates were set: 2, 4, and 6 g/sec. Technical grade nitrogen was used as the working gas. The current was varied from 40 to 900 A, which corresponded to a power variation of from 30 to 220 kW. When the similarity numbers are chosen correctly, variation in the gas flow should not introduce a systematic error that would fall outside the general deviation of the experimental points from the regression line caused by random factors and inadequacy of the approximation dependence. Quantitatively, the value of this systematic error can be estimated from Fisher's inadequacy criterion [1]. To do this, we consider the difference between the sum of the squared residuals of the regression with the consideration of all flow rates and the sum of the squared residuals after correlation of the data for each of the flow rates separately. Taking into account the corresponding degrees of freedom, we define the inadequacy relationship and compare it with the table value. Data on the deviations for the separate flow rates and for all flow rates are presented in Tables 1 and 2 for approximations of the form $U = AI^{\alpha}$ and $U/I = A(G/I^2)^{\alpha}$. Inasmuch as the values of the diameter and scaled quantities are constant in the case under consideration, the dimensional form of the U/I ratio represents the resistance $Ud\sigma_0/I$. In an analogous manner, instead of the convective heat transfer number $Gd\sigma_0 h_0/I^2$ we use the G/I^2 ratio.

It is evident from Table 2 that the VAC of the plasmatron is not described by a single curve. An especially pronounced difference is observed when one uses simple empirical formulas in which for all flow rates the correlation over G is not used. The similarity is improved substantially when the VAC is approximated in dimensional complexes corresponding to dimensionless similarity numbers. In this case the total scatter of points decreases substantially due to correlation over G. The ratio of Fisher's criteria of inadequacy and regression decreases from 1471 to 12%. This result substantiates the advantage of the approximation of the experimental data using methods of approximate similarity.

The mean-square deviation, however, appears to be greater when one generalized argument is used than in the case of two nongeneralized arguments, if a correlation of the following type is used: $U = AI^{\alpha}G^{\beta}$. This is connected with the fact that convective heat transfer is dominant but not the only type in intensely blown-off arcs. Therefore, in order to provide a good correlation of the VAC of such plasmatrons one should use also other similarity numbers that characterize different types of heat transfer. In a number of cases, nevertheless, the number only $Gd\sigma_0 h_0/I^2$ can be used for initial approximations.

In the case considered the diameter of the anode remained constant. Therefore it seems to be appropriate to consider the effect of the gas flow rate when generalizing the characteristics of plasmatrons with different electrode diameters. Such an analysis is given with the linear plasmatron with two tubular electrodes as an example. Data were processed using simple empirical formulas and in generalized variables. In order to reflect the effect of the gas flow rate as a regime parameter and to exclude the effect of the electrode diameter, empirical approximations were taken as $U = AI^{\alpha}d^{\gamma}$ for each of the electrodes, and for the whole set of flow rates. The generalized formula has the form $Ud/I = A(Gd/I^2)^{\alpha}$. The regression parameters are presented in Table 3, and Table 4 presents the discrepancy of the approximation curves for various gas flow rates.

The data from the tables testify that variations in the electrode diameter do not affect the good generalization of the VAC of plasmatrons over the gas flow rate. As in the case of the plasmatron with the rod-like cathode, the correlation coefficients and Student's quantiles increase sharply, and Fisher's ratio for that regression is increased particularly sharply when the generalized variables are used. The mean-square deviation from the regression that is common to all flow rates decreases inspite of the fact that, instead of two independent variables, only one is used, which, however, makes it possible to realize a correlation over G. Especially convincing in this case is the change in Fisher's ratio for the stratification of curves over the flow rate. It decreases from 215 to 0.396 when passing from nongeneralized to generalized variables. With the simultaneous sharp increase in Fisher's regression criterion from 2.18 to 1482 their ratio F_d/F_r decreases from 9900 to 0.03%. Comparison of F_r with the tabulated values shows that the use of approximations of the type of $U = AI^{\alpha}d^{\gamma}$ with a varying flow rate is completely inadequate.

The analysis presented here indicates that the application of simple empirical formulas in the generalization of the VAC of plasmatrons with longitudinal gas flow around the arc does not ensure similarity of the characteristics with varying gas flow rate. Passing to dimensionless expressions that contain generalized variables makes it possible to ensure similarity of characteristics. In order to eliminate almost completely the stratification of characteristics over the gas flow rate it is sufficient to use one generalized argument that characterizes convective heat transfer.

NOTATION

d, electrode diameter; G, gas flow rate; I, arc current; U, arc voltage; h, specific enthalpy of plasma; σ, electrical conductivity of plasma.

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