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INFLUENCE OF INTERELECTRODE GAP AND MAGNETIC INDUCTION ON THE VOLTAGE OF AN ELECTRIC ARC MOVING IN AIR UNDER THE ACTION OF A MAGNETIC FIELD

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For arcs that are initiated in an air medium in rotation in a ventilated annular gap and move along parallel electrodes under the action of an external magnetic field, the influence of the magnitude of the interelectrode gap and magnetic induction on the discharge voltage is considered. The accuracy of the volt-ampere characteristics of the arc in approximating by means of simple empirical power formulas and with the use of criterial relations between generalized variables is estimated.

In electric arc motion under the action of a magnetic field in an annular gap or between parallel electrodes, only the size of the interelectrode gap is limited. The length of the arc column and its cross-section depend on the discharge conditions. The arc length is normally larger than the distance between the electrodes, since the discharge travels with a slope. The slope of the arc and the shape of the cross-section are governed by the interaction of electromagnetic and gasdynamic forces. Therefore the electrical resistance of the arc depends on electromagnetic, gasdynamic, and geometric parameters.

A theoretical calculation of the arc discharge in question is practically impossible at present, and, to describe its volt-ampere characteristic (VAC), approximate expressions are used that are obtained on the basis of experimental data. Both simple empirical; formulas and criterial dependences between generalized variables that are similarity numbers are employed. Power expressions are usually used.

The generalized dependences are convenient because of the fact that they allow for the dominating processes of energy transfer and force interactions. However, when similarity numbers are formed, we have to face the problem of determining the characteristic values of discharge parameters, which should be constant quantities or known variable arguments. Among these known quantities should also be the sizes of the arc column, which are in fact functions of other actually known parameters of the discharge. It is only the interelectrode gap and its curvature that are prescribed dimensional parameters. Therefore, the values of the interelectrode gap and radii are used as characteristic sizes in the similarity numbers. To allow for the dependence of variable sizes of the arc column on the discharge conditions, we have to increase the number of generalized arguments.

The number of the arguments in turn is limited both by the number of initial dimensional variables and by the convenience of obtaining and using a formula. Clearly when sufficient accuracy is observed it is desirable to allow for the smallest number of generalized arguments possible. These approximate formulas have a spread in the initial parameters. Usually in the literature, when generalized VACs are described, insufficient attention is paid to analysis of the influence of the initial variables on the accuracy of formulas. To have an idea of the significance of this problem, in this work we analyze the influence of the magnitude of the interelectrode gap and magnetic induction on the spread in generalized VACs.

In arcs that move under the action of an external magnetic field, the leading part in the forming of VACs is played by processes of convective, conductive, and turbulent energy transfer. The corresponding similarity numbers appear as:

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TABLE 1. Regression Parameters for Generalized VACs of a Transversely Blown Electric Arc Under Different Conditions of Heat Transfer

Generalized argument	Character of discharge	Regression parameters			
		S_e	R	t	F_{reg}
Convection	annular	0.030	0.994	121	14,551
	railtron	0.071	0.982	71	4993
Conduction	annular	0.077	0.958	45	2018
	railtron	0.090	0.974	58	3368
Turbulence	annular	0.051	0.982	70	4842
	railtron	0.065	0.987	81	6601

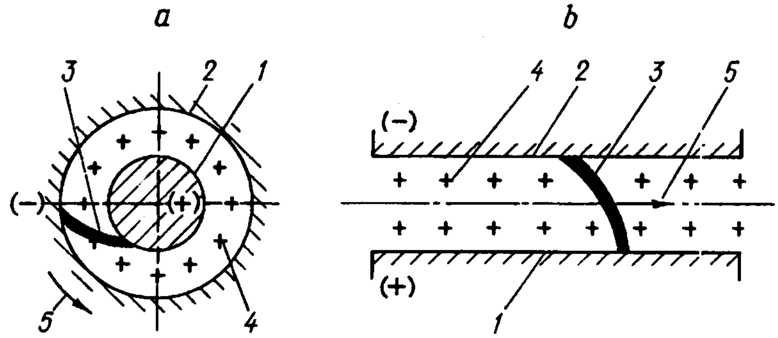

Fig. 1. Discharge devices with arc motion under the action of a magnetic field in an annular gap (coaxial plasmatron) (a) and along parallel electrodes (railtron) (b): 1) anode, 2) cathode, 3) electric arc, 4) external magnetic field lines, 5) direction of arc motion.

$$\pi_{\mathrm{conv}} = \rho_0 h_0^2 \sigma_0^2 L^5 B / I^3 ,$$

$$\pi_{\mathrm{cond}} = \sigma_0 \lambda_0 T_0 L^2 / I^2 ,$$

$$\pi_{\mathrm{turb}} = \rho_0 \sigma_0 h_0^{1.5} L^3 / I^2 .$$

Their relative significance under certain conditions of arcing can be determined by comparing regression parameters when arguments that reflect different mechanisms of heat transfer in the arc column are used in generalized VACs. The most convenient estimation of the relative significance of individual arguments is a comparison of partial values of the variance ratio according to Fisher, which show which part of the total sum of the squares of deviations from the average one is eliminated by correlation between a function and a given argument. However when several generalized arguments are used they turn out to be strongly correlated, since they include common dimensional variables. Therefore, for most nondimensional parameters, this relation is substantially distorted unless special experiments that ensure the independence of individual parameters are conducted. The use of generalized parameters makes it possible to reduce the number of arguments without substantial sacrifice of the accuracy of approximating expressions.

In our case, the maximum number of arguments of the approximating expression is equal to three since three variables – the current, the interelectrode gap, and the induction of the external magnetic field – were varied in the experiments. We consider here the influence of different factors on the accuracy of the obtained formulas for reduction or the number of generalized arguments to one. We will estimate the relative significance of the numbers by comparing the regression parameters. This comparison for an air arc that rotates in a ventilated annular gap (Fig. 1a) and moves along parallel electrodes (Fig. 1b) is given in Table 1. For a plasmatron with an annular gap, we used our experimental data, while the data on the VAC of an arc that moves along parallel electrodes are taken from [1].

From the table, it can be seen that in the case of arc rotation in an annular gap, the best correlation of the experimental data is obtained when the criterion π_{conv} is used as generalized argument, while for a railtron, the criterion π_{turb} turned out to be dominating. The criterion of conductive energy transfer ranks last for both discharge devices. This result is clearly determined by all the regression parameters, but the variance ratio according to Fisher F_{reg} is the most sensitive.

The difference in the dominating processes depends to a certain degree on the character of the discharge devices: in a railtron, the arc moves in a cold gaseous medium, while in the annular gap, the arc runs against the intrinsic trace of the heated gas. However, this difference was to a large measure eliminated by ventilation of the annular gap by forced cold air. The difference in the discharge parameters can turn out to be more substantial: in the railton as compared to the annular gap, we used larger values of the interelectrode gap and smaller magnitudes of the induction of the magnetic field directed perpendicularly to the discharge current. For nearly the same range of change in current, the gap varied from 12.7 to 38 mm in the railtron and from 3 to 6 mm in the annulus. Correspondingly the magnetic induction changed from 0.012 to 0.108 Ts in the railtron and from 0.085 to 0.290 Ts in the plasmatron with the annular electrode. The current increased from 135 to 1000 A in the railtron and from 200 to 800 A in the annular gap. Larger interelectrode gaps in the railtron could increase discharge destabilization.

The difference in the dominating criteria hinders the comparison of the influence of the interelectrode gap on the VAC of the arc in the two types of discharge devices in question. However it is small: both mechanisms of energy transfer – convective transfer and turbulent transfer – have a substantial effect on the VAC of the discharge in transversely blown arcs.

The commonly used regression parameters, given in Table 1, provide an overall estimate of the exactness of the formula, including both the spreads in data due to random factors and the deviations induced by the inadequacy of the approximation and separation by individual independent variables. To estimate the inadequacy of the approximation expression, we need to significantly complicate the experiment through repetition of individual points, which makes it possible to determine the spread due to random factors [2]. We can estimate the separation quantitatively by common experiments, too, assuming that the entire spread about individual curves is caused by accidental reasons, i.e., attributing the inadequacy of the approximations of individual separated curves to a number of random factors. The separation can be estimated quantitatively by the magnitude of the ratio of the separation variance S^2_{sep} to the variance of the random deviations S^2_{r}:

$$F_{\text{sep}} = S^2_{\text{sep}}/S^2_{\text{r}} \,. \tag{1}$$

If F_{sep} turns out to be smaller than the tabulated value of the Fisher number for the prescribed values of the degrees of freedom, the separation does not fall outside the limits of the random spread, and we can disregard it. In this manner, we estimate qualitatively the effectiveness of the function's similarity by individual independent variables when a generalized argument is used.

The variance S^2 is defined as the ratio of the sum of the squares of deviations from the regression SS due to some factor to the corresponding number of degrees of freedom N. Then $S^2_{\text{sep}} = SS_{\text{sep}}/N_{\text{sep}}$; $S^2_{\text{r}} = SS_{\text{r}}/N_{\text{r}}$. The sum of the squares of the deviations due to separation can be determined as the difference of the sum of the deviations from the general curve and the total sum of the squares of the deviations due to the random dispersion $SS_{\text{sep}} = SS_{\text{t}} - SS_{\text{r}} = SS_{\text{t}} - \sum\limits_i SS_i$. Here SS_i is the sum of the squares of the deviations from the individual curves that are induced both by random processes and the inadequancy of the approximation. Similarly we find the number of degrees of freedom $N_{\text{sep}} = N_{\text{t}} - \sum\limits_i N_i$.

Tables 2 and 3 give data on the regression parameters for different values of the interelectrode gap and magnetic induction, respectively, for both types of the discharge devices. Unlike Table 1, the values of the sums

TABLE 2. Regression Parameters for Generalized VACs of a High-Current Air Discharge for Annular and Rail Electrodes for Different Arguments and Sizes of the Interelectrode Gap

Type of discharge device	Generalized argument	L, mm	Regression parameters				
			SS	N	Δ	R	F_{reg}
Annular gap	Convection	3	0.2523	80	0.003	0.982	4376
		6	0.4073	99	0.004	0.974	3779
		total	0.8229	181	0.005	0.988	15,253
	Turbulent	3	1.2505	80	0.016	0.910	819
		6	1.2703	99	0.013	0.920	1144
		total	2.5256	181	0.014	0.964	4848
Railtron	Convection	12.7	0.8413	39	0.022	0.964	661
		19.1	0.7833	33	0.024	0.945	572
		25.4	0.9325	29	0.032	0.954	598
		32.9	1.4095	32	0.044	0.904	302
		38.0	1.2735	40	0.031	0.887	314
		total	5.3044	181	0.029	0.965	4993
	Turbulence	12.7	1.1055	39	0.028	0.927	494
		19.1	0.7816	33	0.024	0.946	573
		25.4	0.6119	29	0.021	0.969	927
		32.0	0.4141	32	0.013	0.972	1103
		38.0	0.8614	40	0.022	0.924	483
		total	4.0471	181	0.022	0.973	6601

of the squares of the deviation from regression and the numbers of degrees of freedom are also listed. From these data we can calculate the values of SS_r, N_r, S_t, and N_t. To determine the values of SS_{sep} and N_{sep}, the tables also show the corresponding parameters for the entire mass of points. The corresponding parameters are given for generalized VACs when the criteria of both convective heat transfer and turbulent heat transfer are used as arguments.

The data of Table 2 confirm the above assumption that the difference in the dominating criteria for the annular gap and the railtron is really due to the size of the interelectrode gap. For $L = 12.7$ mm, convective heat transfer prevails in the railtron, for $L = 19.1$ mm, the indicators of convective heat transfer and turbulent heat transfer level off, and as the interelectrode gap increases further the role of turbulence enhances. The same tendency is evident when the discharge with the annular gap is used as an example. The growth in instability with the length of the arc is due to attenuation of its stabilization by electrode jets of the evaporating material.

Comparison of the generalized formulas with empirical ones (data are not given here) shows that, for individual values of the interelectrode gap, the empirical formula yields a better accuracy of approximation, but in this case a larger number of the arguments (two instead of one in the generalized formulas) is used. For the entire mass of points in the empirical formulas we need to use just three arguments, including the interelectrode gap, in order to obtain good accuracy. At the same time in the generalized formulas for only one argument the magnitude of the error for all the gaps together differs little from the error for the individual interelectrode gaps, the correlation factors and the variance ratios $F_{\text{reg}} = S^2_{\text{reg}}/S^2_{\text{dev}}$ increasing for the entire mass of points. This shows that the generalized formulas ensure rather good similarity in the interelectrode gap in spite of the strong influence of the size of the gap on the arc discharge voltage.

TABLE 3. Regression Parameters for Generalized VACs of a High-Current Air Discharge for Annular and Rail Electrodes for Different Arguments and Values of Magnetic Induction

Type of discharge device	Generalized argument	B, T	Regression parameters				
			SS	N	Δ	R	F_{reg}
Annular electrodes	Convection	0.085	0.1023	42	0.002	0.994	6663
		0.120	0.0569	32	0.002	0.995	6269
		0.170	0.0033	16	0.001	0.999	21,162
		0.236	0.1878	45	0.004	0.989	3940
		0.290	0.1775	38	0.005	0.987	2794
		total	0.8229	181	0.005	0.988	15,253
	Turbulence	0.085	0.0476	42	0.001	0.997	14,373
		0.170	0.0033	16	0.001	0.999	21,163
		0.230	0.0732	45	0.002	0.996	10,176
		0.290	0.0684	38	0.002	0.995	7315
		total	2.5256	181	0.014	0.964	4848
Rail electrodes	Convection	0.012	0.5744	40	0.010	0.990	4038
		0.025	0.1773	33	0.005	0.993	4539
		0.054	0.1113	24	0.005	0.993	3489
		0.080	0.1378	30	0.005	0.993	4118
		0.108	0.4837	46	0.011	0.990	4855
		total	5.3044	181	0.029	0.965	4993
	Turbulence	0.012	0.1737	40	0.004	0.995	8747
		0.025	0.0580	33	0.002	0.995	14,429
		0.054	0.0289	24	0.001	0.998	14,557
		0.080	0.0386	30	0.001	0.998	15,591
		0.108	0.1840	16	0.004	0.998	12,312
		total	4.0471	181	0.022	0.973	6601

a constant value of magnetic induction the spread in the experimental data turns out to be higher for the convective argument than for the turbulent one. However for the entire mass of points the employment of the criterion of convective heat transfer retains a root-mean-square deviation nearly at the level of individual values of magnetic induction for a substantial increase in the variance ratio F_{reg}. Conversely, when the criterion of turbulent energy transfer is employed for the entire data array the spread increases sharply as compared to individual values of magnetic induction, F_{reg} decreasing, too. This dependence is due to the absence of magnetic induction in the criterion of turbulent energy transfer. Unlike the interelectrode gap, no certain regularity in the dependence of the accuracy of the correlation on magnetic induction is observed.

The quantitative estimates of the separation of generalized VACs by the values of the interelectrode gap and magnetic induction for different approximation methods that are calculated from the data of Tables 2 and 3 as well as determined similarly for the empirical formulas are given in Table 4.

Table 4 shows that, for small sizes of the annular gap, F_{sep} by the criterion of convective heat transfer exceeds T_{tab}. The effect of the change in the interelectrode gap in this case falls outside the limits of random error. The use of the criterion of turbulent heat transfer yields a larger spread in the experiment data about the regression. In this case, the change in the gap turns out to be within the random error. Therefore, for small interelectrode

TABLE 4. Values of Variance Ratios for Different Methods of Approximating VACs for Discharges in an Annular Gap and a Railtron

Type of discharge device	Form of approximation	Variance ratios			
		F_{reg}	F_{sep} by L and by B	F_{tab}, %	
				5	I
Annular gap	Generalized VAC in convection	15,253	22	3.05	4.73
			12	1.99	2.61
	Generalized VAC in turbulence	4848	0.17	19.5	99.5
			221	1.99	2.61
	Empirical formula	31	1366	2.66	3.89
			181	1.82	2.30
Rail electrodes	Generalized VAC in convection	4993	0.27	19.5	99.5
			56	1.99	2.61
	Generalized VAC in turbulence	6601	1.56	1.99	2.61
			159	1.99	2.61
	Empirical formula	32	352	1.81	2.29
			146	1.81	2.29

gaps, we should use the number of convective heat transfer as the dominating criterion. A not very large separation, however, remains when the interelectrode gap changes in size. This separation can be decreased by increasing the number of criteria.

For larger interelectrode gaps in the railtron, stabilization of the discharge by electrode jets becomes weaker and pulsations of its parameters increase. In this case, it is already the number of turbulent heat transfer that turns out to be the dominating criterion. In using it as the only argument of generalized VAC the influence of the change in the gap size does not fall outside the limits of random error and F_{sep} turns out to be smaller than F_{tab}.

When generalizing VAC by the criterion of convective heat transfer the separation by magnetic induction is small but it increases substantially when the number of turbulent transfer is used. In this case, the sharp reduction in the root-mean-square deviation for individual values of the magnetic induction, which is quite evident in Table 3, has an effect. Therefore the net error turns out to be substantially smaller than in the case of constant gaps. When the turbulent argument is used, in which there is no magnetic induction, strong separation by this parameter occurs in the total mass of points. Nonetheless, the action of the magnetic field on the arc voltage turns out to be weaker than that of the interelectrode gap. This is quite evident from the data of Table 4 in comparing the Fisher parameters for separation by the gap and magnetic induction when an approximation by empirical formulas is used.

Conclusions. The size of the interelectrode gap in transversely blown arc discharges that move under the action of a magnetic field affect substantially their stability, which shows up the character of the dominating heat transfer process, too. For small gaps, the jets of evaporating electrode material have a stabilizing effect on the discharge, and it is convective heat transfer that prevails in it. The increase in the gap leads to the attenuation of discharge stabilization and to the dominating mechanism of heat transfer becoming turbulent. These peculiarities should be allowed for when constructing generalized VACs of discharges.

The criteria of convective heat transfer and turbulent heat transfer allow quite well for the influence of the interelectrode gap and the separation by this parameter is insignificant as compared to the correlation between the function and the parameter, though F_{sep} somewhat exceeds the 1% and 5% tabulated values. The criterion of convective heat transfer also allows well for the influence of a magnetic field on the generalized VAC of the discharge. Therefore it seems appropriate to use precisely this criterion as the dominating one, even in the case of large interelectrode gaps, since it ensures a substantially smaller separation of the generalized VAC by magnetic induction, though the number of turbulent energy transfer yields a somewhat smaller root-mean-square deviation from the regression.

NOTATION

L, interelectrode gap; G, air flow rate; F, variance ratio according to Fisher; I, current; N, number of degrees of freedom; S^2, experimental value of variance; SS, sum of squares of deviations; R, multiple correlation factor; Δ, root-mean-square deviation; S_e, random error; t, Student quantile; π, criterion; ρ, density; h, enthalpy; σ, electrical conductivity; B, magnetic induction. Subscripts: dev, deviation; add, additional; cond, conductive; conv, convective; turb, turbulent; sep, separation; r, random; reg, regression; tab, tabulated; 0, scale value.

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