CERTAIN CHARACTERISTICS OF FLUCTUATIONS IN ARC CURRENT AND VOLTAGE AND IN THE BRIGHTNESS OF THE JET IN EDDY-TYPE PLASMOTRONS

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Some experimental data relating to the character of the pulsations taking place in the current (I_t) and voltage (V_t), and also in the brightness of the jet(B_t) at the output of a plasmotron, are presented. The distribution functions of these parameters obey a normal distribution law. The circuit elements and the external characteristics of the supply source have a marked effect on the fluctuations taking place in these plasmotron parameters.

In electric-arc heaters of the eddy type incorporating a long, self-regulating arc, the pulsations taking place in the flow parameters of the heated gas are determined by the instability of the electrical parameters of the plasmotron and supply source. The pulsations in the electrical parameters of such types of plasmotrons are mainly due to the shunting of the arc.

A single plasmotron with eddy gas stabilization (working medium air, electrodes copper, water-cooled) was supplied from dc sources with nominal voltages of 4200 or 825 V. The length of the output electrode was 30 cm for d = 1 cm and 80 cm for d = 2 cm. For plotting the distribution functions f_i, f_u, and f_b we used a statistical amplitude pulse analyzer of the AI-100-1 type together with a converter. The signals from the plasmotron passed through a separating condenser to the converter, which transformed the continuous signal into a sequence of pulses 1 μsec long, the amplitude u' being proportional to the instantaneous values of the signal. The repetition frequency of u' was 10 kc/sec.

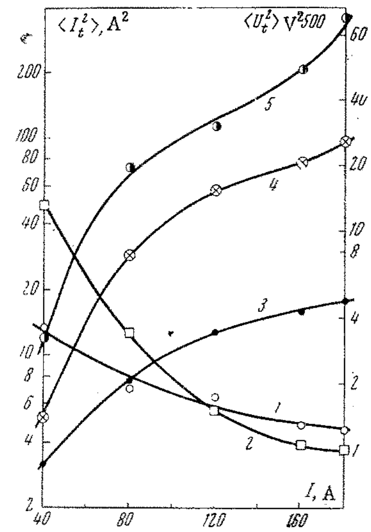

Fig. 1

For measuring the pulsations in jet brightness we used an FÉU-36 photomultiplier. By the "brightness" of the jet we mean the integrated flux of radiation received by the photomultiplier. (In subsequent analysis, B_t will be measured in units of the voltage u' at the output of the converter, which is proportional to the flux of radiation received by the photomultiplier.) The brightness of the jet was measured at a distance of 1 cm from the cutoff point of the output electrode. In order to eliminate the effects of induced currents from the mains network (50 Hz) and fluctuations in the supply source on the results of the experiments, the converter circuit incorporated a filter with a cutoff frequency of 300 Hz.

Analysis of the oscillogram of the distribution function taken from the screen of the AI-100-1 and recorded on film showed that f_i, f_u, and f_b obeyed a normal distribution law, as in [1]

$$f_i = \sqrt{l_i/\pi}\,\exp\left[-l_i(I_s - I)^2\right]$$

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TABLE 1

I,A	U, V	$\langle U_t^2\rangle$,V^2	U *	$\langle I_t^2\rangle$, A^2	I *	G, g · sec^{-1}	d, cm
40	660	2000	6.8	12	8.7	6	1
80	540	1050	6.0	29	6.7		
120	495	700	5.3	42	5.4		
160	450	675	5.8	57	4.7		
180	435	640	5.8	69	4.6		
40	960	2500	5.2	34	14.6	12	
80	720	1150	4.7	78	11.0		
120	645	730	4.2	108	8.7		
160	585	615	4.2	130	7.1		
180	570	520	4.0	150	6.8		
40	1030	1800	4.1	3.3	4.5	6	2
80	675	975	4.6	7.8	3.5		
120	570	865	5.2	13	3.0		
160	465	650	5.5	16	2.5		
180	450	625	5.6	18	2.4		
40	1180	2050	3.8	5.2	5.7	12	
80	825	1020	3.9	29	6.7		
120	750	700	3.5	58	6.4		
160	676	615	3.7	78	5.5		
180	660	575	3.6	96	5.4		
40	1320	5000	5.4	9.5	7.7	18	
80	910	1300	4.0	52	9.0		
120	810	625	3.1	96	8.2		
160	766	550	3.1	150	7.7		
180	750	525	3.1	230	8.4		
40	1440	6500	5.6	12	8.7	24	
80	1000	1700	4.1	74	10.8		
120	885	750	3.1	115	8.9		
160	840	525	2.7	210	9.0		
180	825	500	2.7	360	10.5		

$$f_u = \sqrt{l_u/\pi}\,\exp\,[\,-l_u\,(U_s - U)^2]$$
$$f_b = \sqrt{l_b/\pi}\,\exp\,[\,-l_b\,(B_s - B)^2]$$

over the whole range of measurements of I, G, and d, both for direct polarity (output electrode anode) and for reverse polarity (output electrode cathode); here I, U, and B are the time-averaged values of the arc current and voltage and the brightness of the jet; the indices s indicate the instantaneous values of these quantities. The mean-square deviation of the arc current and voltage and jet brightness are given by the well-known relations

$$\langle I_t^2\rangle = {}^1\!/_2\, l_i, \quad \langle U_t^2\rangle = {}^1\!/_2\, l_u, \quad \langle B_t^2\rangle = {}^1\!/_2\, l_b$$

The resultant values of $\langle U_t^2\rangle$, $\langle I_t^2\rangle$ and correspondingly the quantities

$$U^* = \sqrt{\langle U_t^2\rangle}/U \cdot 100\%, \quad I^* = \sqrt{\langle I_t^2\rangle}/I \cdot 100\%$$

as well as G, d, and I are given in Table 1. It should be noted that the accuracy of the determination of l_u, l_i, l_b depends mainly on the nonlinearity of the converter characteristics; this was no greater than 10%.

Figure 1 shows the dependence of the mean-square deviations $\langle U_t^2\rangle$ (curves 1, 2 for G = 6 and 24 g/sec, respectively) and $\langle I_t^2\rangle$ (curves 3, 4, 5 for G = 6, 12, 24 g/sec, respectively) on the current for d = 2 cm. We see from Fig. 1 and Table 1 that the voltage pulsations diminish with increasing current. The reason for the fall in $\langle U_t^2\rangle$ lies in the reduction in the breakdown voltage of the arc-plasma/anode gap [2]. This may also partly explain [3, 4] the reduction in the mean-square deviations of the brightness (Fig. 2: Curves 1, 2, 3 correspond to G = 6, 12, 24 g/sec, d = 2 cm) if we remember the fact that the pulsations in the brightness of the jet depend on the fluctuations in arc power. Another cause of the fall in $\langle B_t^2\rangle$ with increasing I is evidently the reduction in the arc length and hence in the diffusion of high-temperature arc plasmoids before their emergence from the plasmotron.

An analysis of the experimental data presented in Table 1 shows that for currents up to 120 A $\langle U_t^2\rangle$ increases with increasing gas flow. On further raising the current (I > 120 A) $\langle U_t^2\rangle$ falls with rising G (Fig. 1). The reason for this behavior of $\langle U_t^2\rangle$ is none too certain and requires further investigation. Slightly unexpected was the rise in $\langle I_t^2\rangle$ with increasing arc current. This fact may be explained in the following way.

For the system formed by the arc and the supply source, we may set down the following equation, neglecting the inductance of the circuit and regarding the external characteristics of the source as rigidly fixed:

$$U_b = (I + I_t + CdU_t/dt)\,R + U + U_t$$
$$U_b = IR + U$$

Hence

$$I_t = -\,U_t I/(U_b - U) - CdU_t/dt \tag{1}$$

For C = 0

$$I_t = -\,U_t I/(U_b - U), \quad \langle I_t^2\rangle = [I/(U_b - U)]^2 \langle U_t^2\rangle \tag{2}$$

On varying I from 40 to 180 A (Fig. 1, G = 6 g/sec, d = 2 cm), $\langle U_t^2\rangle$ falls from 1750 to 625 V^2. Thereupon U falls from 1030 to 450 V and the calculated values of $\langle I_t^2\rangle$ for U_b = 4200 V rise from 0.28 to 1.45 A^2, i.e., by approximately a factor of 5.2, while the experimental value of $\langle I_t^2\rangle$ rises by approximately 5.6 times. However, the experimental values of $\langle I_t^2\rangle$ are almost an order of magnitude greater than the calculated values (Fig. 1), i.e., Eq. (2), which makes no allowance for the effect of the shunting capacity, fails to agree quantitatively with experiment, although it correctly reflects the qualitative change in $\langle I_t^2\rangle$ with increasing I.

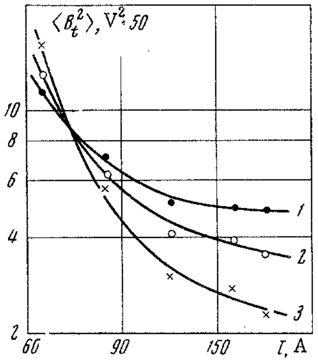

Fig. 2

Thus I_t is considerably influenced by the circuit parameters. At the instant of shunting, U_t falls sharply, and $dU_t/dt < 0$, whereupon the second term in (1) may be much greater than the first. Thus, if the time corresponding to the smooth increase in U_t is of the order of 10^{-3} sec, while $C = 2 \cdot 10^{-6}$ F, $U_b = 4200$ V, $U_t \sim 60$ V, $I = 120$ A, $U = 360$ V (one of the working modes of the plasmotron), then

$$U_tI\,/\,(U_b - U) \approx -1.19 \text{ A} \qquad CdU_t\,/\,dt \approx -0.12 \text{ A}$$

whereas, under the same conditions, but for the time corresponding to the sharp fall in U_t, of the order of $5 \cdot 10^{-6}$ sec,

$$U_tI\,/\,(U_b - U) \approx 1.9 \text{ A} \qquad CdU_t\,/\,dt \approx 24 \text{ A}$$

Here U_b is the supply source voltage, C is the capacity in circuit.

Hence, at the instant of arc–wall or arc–arc breakdown, I_t rises sharply, mainly as a result of the discharge of the shunting capacity. In addition to the large-scale voltage pulsations, there are also small-scale pulsations, and these have a considerable effect on $\langle I_t^2 \rangle$, as shown by the oscillograms of the arc current and voltage.

Considering I_t to be a unique function of U_t, and allowing for C, the expression for $\langle I_t^2 \rangle$ takes the form

$$\langle I_t^2 \rangle = \left[\frac{dI_t(U_t)}{dU_t} \right]^2_{U_t = 0} \langle U_t^2 \rangle$$

At the instant of shunting $U_t = A \exp(-t/r, C)$; hence

$$\langle I_t^2 \rangle = \frac{I^2}{U^2} \left(\frac{U_b - 2U}{U_b - U} \right)^2 \langle U_t^2 \rangle \tag{3}$$

A quantitative calculation using Eq. (3) gives better agreement with the experimental values if $\langle I_t^2 \rangle$. For example, for $I = 40$ A, $U = 1030$ V ($G = 6$ g/sec, $d = 2$ cm) the calculated value of $\langle I_t^2 \rangle \sim 1.3$ A while the experimental value is 3.3 A (Fig. 1). Thus in exact calculations of $\langle I_t^2 \rangle$ we would allow for the effect of the shunting capacity and the voltage pulsations associated with shunting the arc.

It should be noted that on feeding the plasmotron from different sources ($U_b = 4200$ and 825 V) there were no substantial changes in the character of the fluctuations U_t, whereas it follows from Eq. (1) that I_t depends very considerably on the external characteristics of the source of supply, as confirmed by analyzing the oscillograms of U_t and I_t. On feeding the plasmotron from the $U_b = 825$ V source, the first term in (1) had a decisive influence on the character of the current fluctuations.

In our experiments we noted considerable fluctuations in the current of the plasmotron due to fluctuations in the supply source. Allowing for changes in U_b we find from (1) that

$$I_t = U_{bt}I/(U_b - U) - U_tI/(U_b - U) - CdU_t/dt \tag{4}$$

It is thus clear that, on increasing the current, I_t may become very large and affect the operating stability of the plasmotron and also the pulsations in the parameters of the hot gas flow.

Analysis of the $I + I_t$ oscillograms obtained with the supply source ($U_b = 825$ V) loaded into a theostat and with the plasmotron in operation respectively shows that, for the same current in the circuit, the pulsations I_t are much greater with the plasmotron working. In the other source ($U_b = 4200$ V) the value of $U_tI/(U_b - U)$ was insignificant.

Thus, in the range of variation of the parameters of a single-chamber plasmotron of the eddy type studied, the distribution functions of the fluctuations in arc current, arc voltage, and jet brightness obey the normal distribution law. This form of the distribution functions is independent of the polarity of the plasmotron electrodes. The mean-square values of $\langle U_t^2 \rangle$ and $\langle B_t^2 \rangle$ diminish with increasing I, while the values of $\langle I_t^2 \rangle$ become greater. The character of the fluctuations I_t is considerably affected by the parameters of the supply circuit and the external characteristics of the source.

LITERATURE CITED

1. A. S. An'shakov, G. Yu. Dautov, G. M. Mustafin, and A. P. Petrov, "Study of pulsations in a plasmotron with a self-stabilizing arc," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 1 (1967).
2. G. Yu. Dautov, M. F. Zhukov, G. M. Mustafin, and A. N. Timoshevskii, "Study of electrical breakdown in arc-plasma/cold electrode gap," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 2 (1969).
3. G. R. Jordan and L. A. King, "The nature of fluctuations present in dc plasma jets in argon and nitrogen," Brit. J. Appl. Phys., 16, No. 4 (1965).
4. A. M. Trokhan, "Photographic studies of pulsations in plasmotrons with air stabilization," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 2 (1964).