DYNAMICS OF ELECTRICAL PARAMETERS OF AN ARC AND ITS BEHAVIOR IN A PLASMATRON CHANNEL

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Stability of burning of the arc in a plasmatron channel depends on the dynamic as well as the static characteristics of the arc. Many investigations show that the dc arc in a plasmatron is not a stationary phenomenon: the current, the voltage, and also the length of the arc in the channel are all subject to oscillations. Steady pulsations of the electrical parameters are due primarily to the arc shunting process. Nonstationary processes also exist that are not connected with shunting. To speak in terms of a region of the U–I characteristics it can be said that greatest interest centers on the dynamical processes on the rising part of the characteristic. It has previously been shown [1] that the rising branch of the E–I relation has local regions where the electric field intensity of the arc falls with increasing current, such singularities failing to be reflected by the overall static U–I characteristic. This process whereby the overall volt–ampere characteristic is "smoothed out" is connected with certain variations in the structure of the arc in the channel and with the appearance of electrical oscillations. The present paper presents the results of an experimental study of the electrical parameters of the arc in a plasmatron channel and its behavior for a rising volt–ampere characteristic. The rising part is found to exhibit unstable regions, where the arc current and voltage "oscillate." The structure of the arc in the channel changes sharply under unstable conditions. The reason for the appearance of instability is the singularity in the variation of electric field intensity with current on the rising portion of the characteristic.

1. The plasmatron scheme on which the experiments were carried out is shown in Fig. 1. The end electrode (the cathode) is made from thoriated tungsten soldered into a copper ring. To prevent intense erosion of the cathode during operation the latter is protected by nitrogen (G = 2-3 g/sec), continuously supplied to a corresponding vortex chamber. The working gas was air. The output electrode (the anode, of diameter D) is made of copper. The electric field intensity of the arc was measured by constructing a part of the arc chamber of length l and diameter d out of sections of thickness $\Delta l = 0.8$ cm. The length of the first section, constituting the channel input, was 1.5-2 gauge.

All sections were electrically insulated from each other by glass-fiber discs. The experiments were carried out for two values of the internal diameter of the channel, d = 2.5 and 3.0 cm. The diameter of the output electrode was chosen so that the ratio D/d remained constant at 1.8-1.9. The sections used in the electric field measurements were air cooled; all other units of the plasmatron were water cooled. The flow rates of the working and protective gases were measured respectively using a DMKV flowmeter and an RS-5 rotameter.

The variation of the electric field intensity of the arc with current in time was studied using a CI-17 double-beam oscilloscope. One of the beams recorded the alternating component of the arc current I_t. The potential difference between two sections ΔU_t was fed to the other beam via a differential amplifier (Fig. 1). The oscillograms obtained in this manner reflect the dynamic dependence of E on I over a short interval of time (of the order of 10^{-4} sec).

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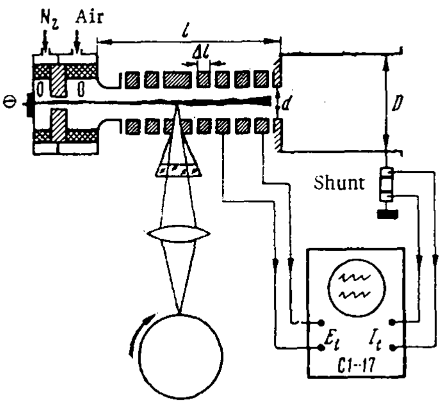

Fig. 1

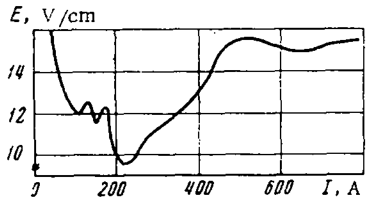

Fig. 2

The spatial behavior of the arc in the plasmatron channel was investigated using a special optical section with a transverse slit on the whole diameter of the channel. The oscillations of the arc column in time were recorded on an FR-1 photorecorder as shown in Fig. 1. In these experiments the plasmatron and the photorecorder were rigidly fixed together. The amplitude-frequency characteristics of the alternating components of the current I_t and the total (overall) arc voltage U_t were displayed on an SK4-3 analyzer. Oscillograms of I_t and U_t were also obtained using an OK-17M oscilloscope. The static volt–ampere characteristics of the arc of the investigated plasmatron and their dependence on various parameters are described in [2].

2. The shunting-induced fluctuations of the electrical parameters of a plasmatron arc with self-setting length are described in [3]. It was shown that these oscillations are random and conform to a normal distribution. In general this is also the case for fixed-length arcs in modes of operation both on the falling and on the rising branches of the volt–ampere characteristic. Besides this, however, the arc current and voltage oscillations exhibit certain features that belong solely to individual regions on the rising branches of the U–I characteristics. It is almost impossible to specify these regions from a consideration of the overall (integral) volt–ampere characteristic. The appearance of unstable zones is connected with the dependence of the electric field intensity on arc current [1].

By way of example, we show in Fig. 2 the E–I characteristic of part of the arc burning in a channel d = 2.5 cm, G = 30 g/sec. It can be seen that the field intensity varies nonmonotonically with current; regions in which E falls with increasing I are also present on the rising curve. One would expect, on the basis of the results of the E investigations, that the rising branch of the overall volt–ampere characteristic would also have regions in which the voltage U falls with increasing I. It can be seen from Fig. 3 (curve 1) that the U–I relation for the greater part of the arc length does have these singular regions; curve 1 is the volt–ampere characteristic of the part of the arc extending from the cathode to the anode shoulder.

The integral (overall) volt–ampere characteristic for the entire arc is shown by curve 2. The changed form of the latter compared with curve 1 is due partly to the U–I characteristic of the initial part of the arc in the vicinity of the vortex chamber, and partly to the U–I characteristic of the output part of the arc in the channel of diameter D. As was noted in the experiments, the smoothing-out of the overall volt–ampere characteristic is due primarily to the dynamics of the behavior of the arc column in regions of intensity drop. The oscillations of I_t and U_t can be quite varied in character. Thus, we show in Fig. 3 oscillograms of the alternating component of the arc voltage taken in the regions: b-c (I), c-d (II), and d-e (III). They demonstrate the behavior of the oscillations of U_t associated with shunting on different parts of the U–I characteristics (d = 2.5 cm, l = 14.5 cm, G = 60 g/sec). While the form of oscillograms I and III is typical for the shunting process, with its characteristic increase of voltage with increasing arc length and subsequent sharp drop, this cannot be said about oscillogram II. In the latter case almost square pulses of U_t are observed, for which various explanations are possible on account of the instability of burning of the arc. It should be noted that oscillogram II cannot, generally speaking, be said to be typical, unlike oscillograms I and III. In the region of instability, the arc voltage and current can exhibit quite a variety of waveforms; there is, however, one distinctive feature – these waveforms are qualitatively different from those associated with "pure" shunting.

If the smoothing-out of the overall static volt–ampere characteristic is due to the periodic shunting-induced variation of the length of the arc, then time intervals must exist under dynamic conditions when the dependence of voltage on current will have a diminishing form determined by the behavior of $E = f(I)$. In this connection it is particularly important to know how the electric field intensity of the arc varies as a function of current under dynamic conditions. If one starts from the equation of the dynamic characteristic [4] and considers perturbations acting on the arc that have a period greater than the characteristic relaxation time, it follows that the dynamic characteristic will be determined by the behavior of the static U–I characteristic. However, the question is to what extent does the dynamic variation of the intensity E as a

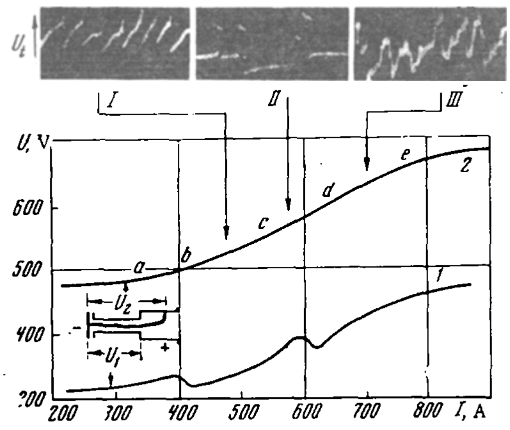

Fig. 3

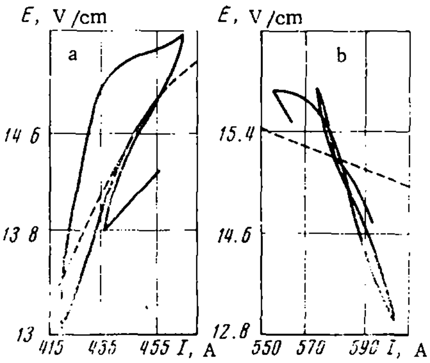

Fig. 4

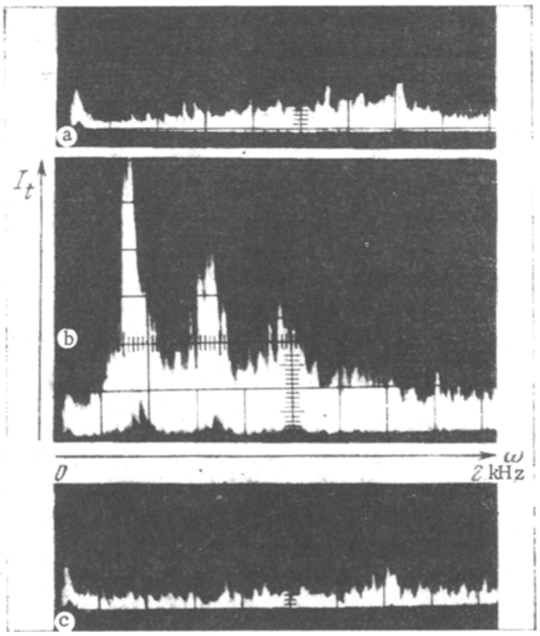

Fig. 5

function of I correspond to the static characteristic, since oscillations of arc length on the measurement basis can give rise to a certain discrepancy between them.

Experiments on the arc dynamics were carried out in the manner described above. An analysis of many oscillograms showed that the dynamic characteristic has a slope that is quite close to that of the tangent to the static E−I curve only on the rising part of the latter. This can be observed from Fig. 4, which shows the dynamic E−I characteristics for d=2.5 cm and G=30 g/sec; a is the rising and b the falling part.

The dashed curve in Fig. 4a refers to the static E−I relation. In the region where E decreases with increasing I (Fig. 4b) it can be seen that the dynamic curve has a much steeper slope than the static. Thus, a 50-A variation of current changes E according to the static characteristic by only 0.4 V/cm (see dashed line in Fig. 4b), whereas according to the dynamic characteristic we find that $\Delta E \approx 2$ V/cm. This sort of E dynamics was also experimentally observed for other values of the working parameters of the plasmatron and is also present on the E−I characteristics of the initial part of the arc.

The obtained data show that, despite the smoothing-out of the overall volt−ampere characteristic of the plasmatron arc, regions in which the arc voltage drops with increasing current exist under dynamic conditions on the rising part of the U−I characteristic.

3. Let us consider the features of the oscillations of the electrical parameters of the arc on the rising branches of the U−I characteristics in regions of instability. As was shown above the appearance of regions of instability on the volt−ampere characteristic is connected with a change in the form of the E−I relation, the distinctive feature of these regions being the presence of a negative differential arc resistance R^*. Under certain conditions this leads to the appearance of undamped oscillations of current and voltage. The arc can go over into an oscillation mode on violation of one of the stability criteria [5], for example, the inequality $R+R^* > 0$, where R is the ohmic resistance in the plasmatron supply circuit. Our previous investigations [1] and also the dynamic characteristic of the arc (see Fig. 4b) indicate that very large negative values of R^* can indeed be achieved in the second region of instability on the rising branch of the volt−ampere characteristic (for example, the region c–d in Fig. 3). Accordingly, undamped oscillations of arc current and voltage should appear in this region for plasmatrons with various working parameters and for almost any value of R, which checks out experimentally.

Figure 5 shows traces of the amplitude−frequency characteristic of the arc current oscillations for d=3.0 cm, l =24 cm, G=80 g/sec; I=650 A (a), 850 A (b), 1200 A (c). The power supply was a generator

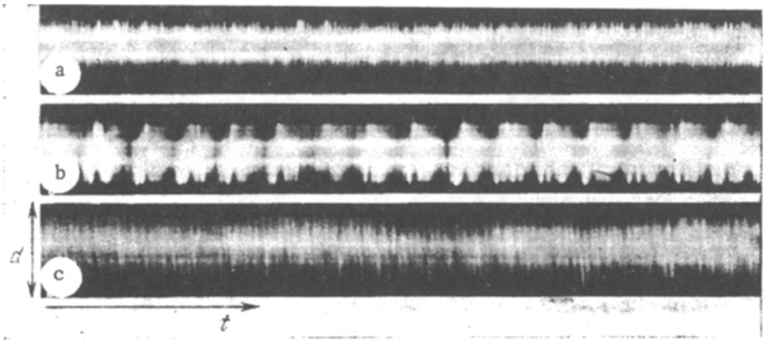

Fig. 6

with a nominal voltage of 750 V. For the given values of G, d, l, the second region of instability about the minimum of the volt–ampere characteristic lies in the region of 800-900 A.

Traces a and c show the spectrum of the oscillations at currents of 650 and 1200 A, corresponding to a positive characteristic; trace b relates to the region of instability. It can be seen that the spectrum of the oscillations change sharply at 850 A. Whereas in the stable regions the spectrum simply represents the noise induced by the random character of the shunting of the arc in channel D, distinct maxima of I_t are clearly discernible on the trace of Fig. 5b. The amplitude of the current oscillations at the first maximum is almost an order of magnitude greater than the I_t of Figs. 5a, c. It should be noted that the obtained spectrum (Fig. 5b) is not the result of power-supply oscillations, the frequency of which is 1500 Hz. Traces of the arc voltage oscillations taken under the same conditions of operation of the plasmatron show that U_t behaves in a similar manner.

The spectrum of the expanded signals is of considerable interest. Indeed, the arc in a plasmatron (represented as an inductance, capacitance, and ohmic resistance) together with the elements of the supply circuit constitutes a tuned circuit resonating at a frequency ω_0. The oscillations of I_t and U_t produced upon excitation of this circuit should have a sinusoidal form and the spectrum of the signals a single maximum at the frequency ω_0. The trace of Fig. 5b clearly discloses, however, four maxima, at frequencies ~ 320, 640, 960, and 1280 Hz; i.e., frequency multiples of 2, 3, and 4 are present. The amplitude of I_t falls off approximately as 1/n. Thus, the spectrum does not correspond to the expansion of a sinusoidal signal but, for example, to the expansion of an approximately sawtooth waveform. This suggests that the generated signals are formed by a process involving a certain motion of the arc, there being no other likely explanation. Accordingly, investigation of the spatial behavior of the arc column in a plasmatron channel is of interest with a view to explaining the current and voltage oscillations.

4. We mentioned above the smoothing out of the static volt–ampere characteristic of a plasmatron arc as a result of the appreciable oscillations in the length of the arc. This can also explain the data of Fig. 4b, which show that the intensity as a function of current drops more steeply under dynamic conditions than in the static case, i.e., spatial instability of the arc column should be observed on the investigated part of the E–I characteristic.

Time sweeps of the transverse oscillations of the arc in the plasmatron channel (d = 2.5 cm, G = 30 g/sec) are shown in Fig. 6 [I = 420 A (a), 560 A (b), 700 A (c)]. The distance from the cathode to the cross section of the channel at which the photographs were taken (Fig. 1) equals 8 cm. The velocity of motion of the film was 3 m/sec. An analysis of the photographs shown in Fig. 6 indicates that transverse oscillations of the arc do not occur (Fig. 6a, c) on regions of the rising E–I characteristic (Fig. 2) to the left and to the right of the region of intensity drop. The traces also clearly exhibit high-frequency pulsations, which are very likely the result of the motion of the swirling flow of gas. It can be seen that the luminous diameter of the arc increases with increasing current. The form of the trace changes sharply (Fig. 6b) in the vicinity of the region where E drops with increasing I: distinct deviations of the arc from the center of the channel are observed. The motion of the arc is manifestly periodic: for a certain time the arc is unstable, and deflects from the center of the channel; however, after a time, the arc again takes up a position on the axis, and the process repeats. The trace of Fig. 6b thus has a bunch-like form. The repetition frequency of these bunches is 315-340 Hz. The voltage and current of the arc vary at moments of deviation from the axis, which can also be seen on the expansion spectrum of the signals (Fig. 5b). Estimates of the diameter of the arc column made using the data of Fig. 6b indicate that when the arc is unstable it simultaneously contracts.

The results of a numerical calculation [1] also indicate that a reduction in the transverse dimensions of the arc is possible in the region where E falls with increasing I. It has hitherto not been possible to determine the true reasons responsible for the deviations of the arc from the axis; it can be said, however, that they are not connected with loss of hydrodynamic stability. Let us consider briefly one possible candidate.

In a discussion on the displacement of an arc from the axis, Maecker [6] obtained the following expression for the velocity of the arc relative to the matter, V:

$$(\mathrm{V}\cdot\nabla_m)\,\nabla T = -\,\nabla_m\left\{\frac{1}{\rho c_p}\left(\frac{j^2}{\sigma} - \operatorname{div}\mathrm{W} + a\ldots\right)\right\}$$

where ∇_m is the gradient in the vicinity of the temperature maximum, ρ is the mass density, j^2/σ is the ohmic heating, div W is the heat-conduction loss, $W = -\lambda\nabla T$, and a is the radiative absorption per unit volume.

The arc can be brought into motion by, for example, nonuniformity of the absorption a. In the motion of a nonuniformly heated arc ignoring variation of the temperature maximum T_m, the term on the right side of the above expression corresponding to the gradient div W increases at the maximum and thus retards the motion of the arc. This is a consequence of the change in the curvature of the temperature distribution over the diameter in the direction of displacement of the arc. If one assumes that the thermal conductivity λ in the vicinity of the temperature maximum begins to fall from some moment with increasing T_m, then the gradient div W at the maximum will vary with a change of sign. In other words, the situation can arise when, even for a random deviation of the arc from the axial position, the arc will not return to its initial position but will continue to move towards the wall of the channel. This, reduction of λ with increasing T, is one possible reason in a region where E drops with increasing I. In actual fact the investigated phenomenon is much more complex. The effect of the self-magnetic field of an arc upon its motion probably cannot be ignored.

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