The authors thank D. D. Ryutov for the interest in this study and the valuable comments, also V. S. Koidan and V. M. Lagunov for the helpful discussions, also V. P. Dragunov for the assistance in carrying out the study.

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ELECTRIC FIELD INTENSITY DUE TO AN ARC IN A DEVELOPED TURBULENT AIR STREAM

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UDC 537.523.004.5

In plasmotrons with an interelectrode insert of sufficient relative length there evolve all three regions which characterize the flow of a gas through a tube (initial, transitional, and developed turbulent [1]). As is well known [1, 2], the electric field intensity of the arc differs in these regions. It is technically highest in the third channel region, much higher than in the initial one. Studies of the aerodynamics of gas flow through channels have contributed to the development of simple and highly efficient methods of controlling the length of the initial flow region and thus also that of the turbulent one, making it possible to intentionally influence the integral electrical characteristic of an arc – the voltage. In view of this, there has arisen the necessity to generalize the electrical characteristic of an arc glowing in a developed turbulent stream, i.e., to find how the electric field intensity of an arc in such a stream depends on the current, on the channel diameter, on the pressure, and on the gas flow rate. Such a generalization is important, moreover, because plasmotrons with an interelectrode insert are now the most promising devices of this kind, not only on account of the high power that can be pumped into the arc but also on account of the efficient conversion of electric energy to heat. Meanwhile, however, most theoretical and experimental studies have dealt mainly with arcs glowing in a laminar gas stream. In real plasmotrons of linear configuration with gas-vortex stabilization of the arc, on the other hand, the Reynolds number of the stream is usually higher than critical [3]. Several

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Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 11-16, November-December, 1979. Original article submitted November 28, 1978.

0021-8944/79/2006-0662$07.50

theoretical studies have dealt with arcs in a turbulent gas stream [4, 5], According to these studies, it is noted, small fluctuations of temperature and gas flow rate (4-5%), characteristic of developed turbulent gas flow through a tube, cannot cause an appreciable rise of the electric field intensity of an arc. Only larger fluctuations of these parameters, of the order of 10-20%, can cause the electric field intensity to become 3-4 times higher than in an unperturbed stream [5]. The results of these theoretical calculations agree sufficiently closely with experimental data [6, 7]. However, more recent studies of the arc glow pattern in the initial segment of a channel with developed turbulent flow suggest that the mechanism by which the technical electric field intensity of an arc rises is, most likely, based not only on an intensification of the heat transfer from arc to gas but also on an increase of the real arc length in the gauge segment of the channel. The difficulties in building a theory of an electric arc glowing in a developed turbulent gas stream are largely due to a lack of reliable experimental data on the structure of an arc in this region, on its interaction with the gas stream, etc. The object of this study is to generalize the available experimental data on the electric field intensity of an arc in air, in the region of developed turbulent flow. Such an attempt was already made in another study [8], but omission by those authors of the gas pressure in the generalized equation makes the latter valid only under the conditions (with regard to pressure) of the experiment. There are also several other factors which restrict the applicability of that generalized equation.

1. Experimental Apparatus

The dependence of the technical electric field intensity on the determining parameters was studied in the plasmotron [1] with an interelectrode insert. The inside diameter of the electric-discharge channel was $d = (1, 2, 3)\cdot10^{-2}$ m. In most experiments the cylindrical exit electrode (anode) and the channel had the same diameter. Only for the channel with $d = 1\cdot10^{-2}$ m were sometimes used anodes with a diameter $d_a = 1.4\cdot10^{-2}$ m. The relative length of the interelectrode insert $\bar{a} = a/d$ was varied from 12 to 34 and that of the exit electrode from 2 to 6. The interelectrode insert segments were $1\cdot10^{-2}$ m thick, but with $d = 1\cdot10^{-2}$ m were also used $1.6\cdot10^{-2}$ and $2.1\cdot10^{-2}$-m-thick segments. The intersegmental gap was $(1-2)\cdot10^{-3}$ m wide. The interelectrode insert segments were insulated from one another as well as from the electrodes and cooled, as a rule, with technically pure water. A part of the active gas, G_0 kg/sec, was fed through a curling ring into the electric-discharge channel between the end electrode and the first insert segment. The remainder of the gas was passed through intersegmental curling rings. The gas flow rate between the last insert segment and the anode was somewhat higher, $g_a = (1-3)\cdot10^{-3}$ kg/sec, so as to prevent breakdown here. For the purpose of decreasing the length of the developed turbulent flow region, in most experiments, an agitating stream of gas at the rate g_s was fed into the electric-arc chamber through an intersegmental gap at a distance z_s equal to 1-5 bore diameters from the entrance [2]. The total flow rate of gas (air) through the plasmotron $G = G_0 + \Sigma g_i + g_a + g_s$ was varied from $6\cdot10^{-3}$ to $50\cdot10^{-3}$ kg/sec. The experiments were performed with the arc current I = 40-600 A. Electric power was supplied by a thyratron rectifier (V_0 = 4.2 kV and I_{max} = 200 A) or a mercury-arc rectifier (V_0 = 1650 V and I_{max} = 750 A).

The mean electric field intensity along the channel was determined from measurement of the potential difference between adjacent segments with a model S-50 electrostatic voltmeter of class 1.0 accuracy. It was assumed that the electric potentials at adjacent interelectrode insert segments, operating under similar conditions, corresponded to the arc potentials at the median sections of these insert segments. The gauge length at which the potential difference across the arc was measured, as well as the variation of gas flow rate and gas pressure over that length, remained relatively small so as to make it permissible to assume a uniform electric field intensity over that gauge length. The error in establishing the gauge length due to different thicknesses of the segments and different widths of an intersegmental gap did not exceed ±5%, i.e., the rms error in measuring the electric field intensity was within ±6%. In some cases the electric field intensity was determined from the potential distribution along the channel, which had been plotted on the basis of measurement of the potential at each interelectrode insert segment. The electric field intensity was actually obtained by graphical differentiation of that distribution curve. Despite the satisfactory similarity of both methods, however, the first one was found to be preferable because of the smaller error and because of the better tracking of changes in the electric field intensity along the channel.

2. Results of the Experiments and Their Discussion

Let us examine the distribution of electric field intensity due to an arc (Fig. 1) along a channel with the inside diameter of its electric-arc chamber $d = 2 \cdot 10^{-2}$ m and with an interelectrode insert of the relative length $\bar{a} = 25$. Corresponding to a total flow rate of the active gas (air) $G = (25\text{-}27) \cdot 10^{-3}$ kg/sec and an air flow rate through the intersegmental gaps $g_i = 0.1 \cdot 10^{-3}$ kg/sec at an arc current $I = 100$ A. The dashed-line curve 1 depicts the distribution of electric field intensity in the absence of strong gas injection [2] regulating the length l_0 of the initial flow region. That length, in this particular case, reached 15 bore diameters. The electric field intensity can be regarded as uniform over this region. It begins to rise at $\bar{z} = 15$ and at $\bar{z} \approx 21$ reaches a level more than 3 times higher than within the initial region. For the given value of parameter $\bar{a}$ only a short part of the total channel length, approximately 4 bore diameters, corresponds to the region of developed turbulent flow. Agitation of the stream by intensive gas injection with $m_s = (\rho v)_s/(\rho v)_0 \approx 1$ [2] at the channel section $\bar{z}_s = 4.5$ makes it possible to shorten the initial region to 4 bore diameters (curve 2). Beyond $\bar{z} = 7$, approximately, follows the region of developed turbulent flow. Here the electric field intensity due to arc is found to rise slowly along the channel, owing to a higher gas flow rate. Over the region 21-25 bore diameters the level of electric field intensity due to the arc is almost the same with and without artificial agitation. This signifies that the processes of interaction between the electric arc and the gas stream are the same in both cases. This hypothesis has also been supported by measurement of the distribution of the turbulence level in a cold gas stream along the channel axis with and without artificial agitation. In the former case the turbulence was found to reach a level characteristic of developed turbulent flow in the channel already at a distance of a few bore diameters from the injection point. All this evidence provided a basis for studying the dependence of the electric field intensity due to an arc in a turbulent gas stream on the determining parameters in plasmotrons with short interelectrode inserts (12-14 bore diameters) and, with the possibility of using a relatively low-voltage high-current power supply available, extending the range of operating currents.

When $g_i = 0$, then the gas flow rate behind the point of agitating injection does not change. In this case the experimentally determined electric field intensity was found to be approximately uniform along the channel within the region of developed turbulent flow. When $g_i \neq 0$, then E_T is found to rise downstream (Fig. 1).

In order to account for the dependence of the electric field intensity on the pressure, measurements of the latter were made at several channel sections within the region of developed turbulent gas flow. The readings indicated significant changes in pressure along the channel. Over the distance 10-23 bore diameters it had dropped by more than 30% (from $1.65 \cdot 10^5$ to $1.25 \cdot 10^5$ Pa at $g_i = 0$ and $I = 100$ A).

Typical E_T-I characteristics of an arc in a channel with diameter $d = 2 \cdot 10^{-2}$ m at four different gas flow rates are shown in Fig. 2, for $\bar{a} = 20.2$ and $\bar{z}_s = 2$: 1) $G = 14.8 \cdot 10^{-3}$ kg/sec and $g_i = 0$; 2) $G = 21.4 \cdot 10^{-3}$ kg/sec and $g_i = 0.15 \cdot 10^{-3}$ kg/sec; 3) $G = 25.1 \cdot 10^{-3}$ kg/sec and $g_i = 0.30 \cdot 10^{-3}$ kg/sec; 4) $G = 24.5 \cdot 10^{-3}$ kg/sec and $g_i = 0.37 \cdot 10^{-3}$ kg/sec ($\bar{a} = 14.3$); 5) $G = 36.9 \cdot 10^{-3}$ kg/sec and $g_i = 0.54 \cdot 10^{-3}$ kg/sec.

These E_T-I characteristics are curves which descend over the experimental range of currents. A higher gas flow rate results in a higher electric field intensity. Raising the gas pressure and reducing the channel diameter have the same effect.

The choice of dimensionless criterial numbers for the generalization of experimental data was made on the assumption of the intrinsic magnetic field of an arc in air and the radiation from that arc being weak influencing factors. Accordingly, the determining parameters included the arc current, the gas pressure and flow rate, and the diameter of the electric-arc chamber. The dimensionless criterial numbers used were $S_E = 2(\sigma/\pi\mu h)^{1/2}(Ed)$, $S_I = 2(\pi\mu h\sigma)^{-1/2}(I/d)$, $Re_d = 4G(\pi d\mu)^{-1}$, $Kn = kT/(Qpd)$, with μ, σ, h, T denoting respectively, the characteristic values of dynamic viscosity, electrical conductivity, enthalpy, and temperature for air, k denoting the Boltzmann constant, and Q denoting the effective cross section for scattering of electrons. The experimental data were generalized according to the well-known procedure [2, 9].

The generalized expression for the electric field intensity due to an arc was sought in the form

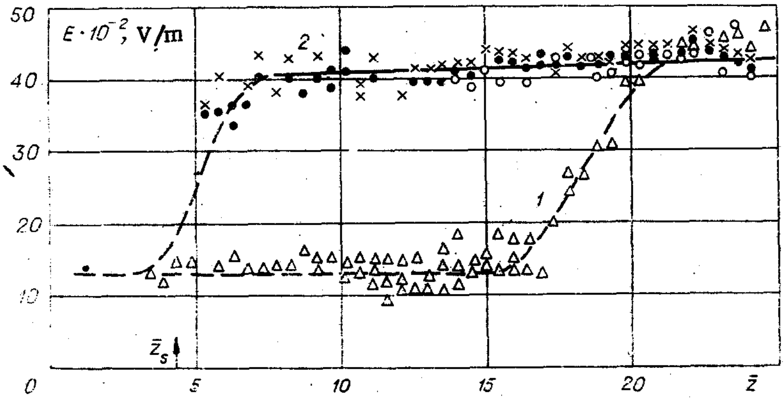

Fig. 1

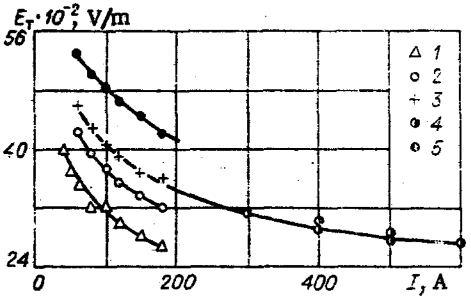

Fig. 2

$$S_{E_T} = C S_I^{\alpha} \mathrm{Re}_d^{\beta} \mathrm{Kn}^{\gamma}.$$

The characteristic values of temperature, enthalpy, dynamic viscosity, and electrical conductivity for air were then assumed to remain constant at $T = 400°K$, $h = 4\cdot10^5$ J/kg, $\mu = 2.3\cdot10^{-5}$ kg/m·sec, and $\sigma = 4.32\cdot10^2$ mho/m (electrical conductivity of air at $T = 6400°K$, according to [2]). The effective cross section for scattering of electrons in an arc, which appears in the Knudsen number, depends on the temperature and can be taken as $Q = 5\cdot10^{-20}$ m^2 for air [10].

An analysis of our data and those in [6] indicates that, within the experimental range of the determining parameters, S_{E_T} can be regarded as being proportional to $(S_I)^{\alpha}$ with exponent $\alpha = -0.23$. For the pressure $p = 11.2\cdot10^5$ Pa and the diameter $d = 0.7\cdot10^{-2}$ m only those data from [6] were used which had been known beforehand to correspond to turbulent gas flow. The dependence of log S_{E_T} on log Re_d would be represented by a straight line with the slope $\beta = 0.47$.

Special attention must be paid to determining the dependence of the electric field intensity due to an arc on the gas pressure. When generalizing the integral characteristics of an arc, one usually chooses the gas pressure at the plasmotron exit as the characteristic gas pressure [2, 9]. In studies of the electric field intensity and other local arc characteristics one must, naturally, take the values of the determining parameters at the section under consideration. In a plasmotron with an interelectrode insert, it has been pointed out earlier, the gas pressure and flow rate can vary appreciably along the channel and differ significantly from those at the plasmotron exit. In the experiments involving electric-arc chambers with diameters $d = 2\cdot10^{-2}$ and $3\cdot10^{-2}$ m, respectively, the gas pressure differed little from atmospheric pressure over the gauge length, while in the case of electric-arc chambers with diameters $d = 1.0\cdot10^{-2}$ m and $d = d_a$, respectively, the gas pressure at the sections under consideration exceeded the gas pressure at the plasmotron exit by $(0.5-0.7)\cdot10^5$ Pa. The dependence of the electric field intensity due to an arc in a developed turbulent stream on the local gas pressure in the channel is shown in Fig. 3, in terms of the dimensionless complex $A = S_{E_T} S_I^{0.23} \mathrm{Re}_d^{-0.47}$ as a function of the Knudsen number. The experi-

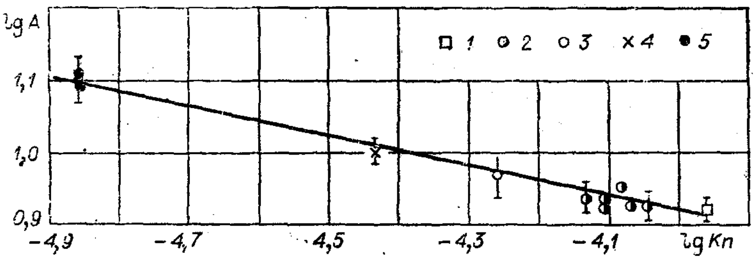

Fig. 3

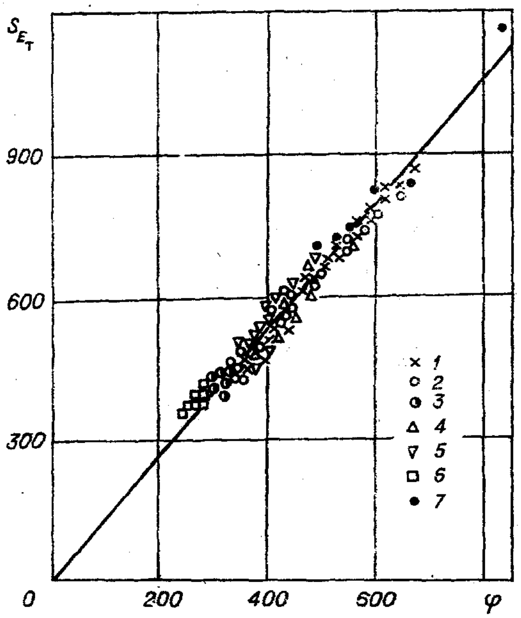

Fig. 4

mental points here pertain to the following values of parameters: 1) $d = 1 \cdot 10^{-2}$ m, $d_a = 1.4 \cdot 10^{-2}$ m, $p = 1 \cdot 10^5$ Pa; 2) $d = d_a = 1 \cdot 10^{-2}$ m, $p = (1-1.7) \cdot 10^5$ Pa; 3) $d = 2 \cdot 10^{-2}$ m, $p = 1 \cdot 10^5$ Pa; 4) $d = 3 \cdot 10^{-2}$ m, $p = 1 \cdot 10^5$ Pa; 5) $d = 0.7 \cdot 10^{-2}$ m, $p = 11.2 \cdot 10^5$ Pa [6]. The dependence of log A on log N_{Kn} can, over the experimental range of parameters, be represented by a straight line with the slope $\gamma = -0.2$. The spread of experimental points seen in Fig. 3 is attributable mainly to errors of pressure measurements within the gauge segment.

The dependence of S_{E_T} on the dimensionless complex $\varphi = S_I^{-0.23} \mathrm{Re}_d^{0.47} \mathrm{Kn}^{-0.2}$ is shown in Fig. 4. Points 1-3 correspond to $d = 3 \cdot 10^{-2}$, $2 \cdot 10^{-2}$, and $1 \cdot 10^{-2}$ m, respectively. On the same diagram are also shown experimental points from [8] for $d = (2.0, 1.5, 1.0) \cdot 10^{-2}$ m (points 4-6, respectively) and from [6] (points 7). For approximately calculating the electric field intensity due to an arc glowing in a developed turbulent stream, we thus have the expression

$$S_{E_T} = 1.34\, S_I^{-0.23} \mathrm{Re}_d^{0.47} \mathrm{Kn}^{-0.2}. \tag{1}$$

The relative deviation of experimental points from the calculated curve does not exceed ±6% over the ranges of critical numbers $S_I = 35-540$, $N_{Re_d} = (2.7-11.0) \cdot 10^4$, and $N_{Kn} = (1.3-11) \cdot 10^{-5}$. The adequacy of expression (1) for calculating the distribution of electric field intensity along the entire region of developed turbulent flow is demonstrated, among others, by the theoretical curve 2 in Fig. 1. Here E_T has been calculated from local gas flow rates and pressures. With the gas flow rate increasing considerably along the region of developed turbulent flow, the relative deviation of experimental points from the theoretical curve does not exceed ±10% at a 0.95 confidence level.

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SATURATION CURRENTS INTO A PROBE IN A DENSE PLASMA

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UDC 533.9.082.76

In connection with intensive studies concerning the flow of an ionized gas, there has now also developed a considerable interest, according to the literature on this subject, in electric probes widely used as a major diagnostic tool. Electric probes are rather simple devices, but difficulties arise in the interpretation of a measured current—voltage characteristic and, especially, when such a probe operates in the hydrodynamic mode, i.e., when the mean free path of particles is much shorter than the characteristic probe dimension and the thickness of the Debye layer. In this study we will theoretically analyze the trend of the current—voltage characteristics of single electric probes in streams of dense plasmas at high positive and negative surface potentials when $\varepsilon = \lambda_d^2/L^2 << 1$ (λ_d denoting the characteristic quiescent Debye radius and L denoting the characteristic scale of change in the hydrodynamic parameters near the probe surface). This problem was for the first time considered in [1], where an asymptotic analysis of it at the limit $\lambda_d^2/\delta^2 \to 0$ (δ denoting the thickness of the viscous boundary layer) has led to the conclusion that the current—voltage characteristic of a probe at high positive (or negative) surface potentials levels off to constant values corresponding to the electron (ion) saturation current. Explicit expressions have been derived for the density of saturation currents which involve the normal derivative of the quasineutral concentration of charged particles at the wall. However, the assumptions made in that analysis greatly limit the applicability of the obtained results and, generally, make them unsuitable for direct diagnosis. It has been assumed in [1], e.g., that the gas temperature and density as well as the transfer coefficients are uniform in space, which implies equal temperatures of the probe surface and the unperturbed stream. In most experiments this condition is not fulfilled, however, since the probe is usually much colder than the plasma unperturbed by it. Collisions between charged particles as well as gaseous-phase ionization and recombination processes have also been disregarded in that study, which is not permissible in the interpretation, e.g., of probe measurements in the plasma of open-cycle MHD generators. It has been, furthermore, assumed in [1] that the gas flows in the boundary-layer mode and, accordingly, it is not possible to interpret, for instance, the probe measurements in a slowly moving plasma of the flame type [2] or the probe measurements under conditions of supersonic streamlining of blunt bodies by weakly charged plasmas in the "viscous shock lay-

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Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 16-24, November-December, 1979. Original article submitted October 25, 1978.

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