# ELECTRIC ARC IN FLOW WITH WELL-DEVELOPED TURBULENCE

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The results of an investigation of electric-arc discharge in a flow segment with well-developed turbulence in a cylindrical channel are given.

In electric-arc devices with longitudinal or transverse blowing on the electric arc, turbulent heat and mass transport exerts a considerable, and sometimes decisive, effect on the shape of the arc and its energy characteristics. Turbulence may arise during dynamic interaction between the gas flow and the arc column, that is, the current-conducting zone, or it can develop in the current-conducting zone itself due to instabilities of a magnetohydrodynamic nature.

Various types of electric arc discharge in a turbulent flow and the turbulence mechanism are discussed in several theoretical and experimental papers [1-3]. However, the physics of turbulence development in the presence of an electric discharge is extremely complex, which probably explains the fact that there is still no satisfactory model of a turbulent arc and that the volume of experimental investigations in this field is very small.

We provide here the results obtained in investigating a relatively simple case — that of electric discharge arcing in a cylindrical channel within the turbulent segment of a gas flow. There are several factors which stimulate interest in such arcs with longitudinal blowing. First, the industry uses a wide range of electric-arc heaters where the arc is exposed to longitudinal blowing. Moreover, the totality of the available experimental data indicates that the development of turbulence in the current-conducting zone is determined by the turbulent boundary layer which forms at the channel wall and spreads toward the axis. In other words, turbulence in this case has a purely hydrodynamic character, and any other possible turbulence mechanisms (for instance, a magnetohydrodynamic mechanism) apparently have no special significance. The initial turbulence that arises at the channel inlet can be either eliminated or reduced to a minimum by means of damping devices or some other means.

Three flow segments are observed in a cylindrical channel where a gas is blown longitudinally around an electric arc: the initial and the transition segments and the flow segment with well-developed turbulence [1].

The initial segment is characterized by an axisymmetric arc whose shape is stable in time and a virtually constant electric field strength along its length. For sufficiently large currents ($I > 100$ A), the heat exchange between the arc column and the ambient is determined to a considerable extent by radiative transport; the thermal flux reaching the channel walls is almost completely determined by radiation from the electric discharge. The transition segment is characterized by the development and the downstream intensification of radial vibrations of the arc as a whole as well as perturbation of the column's axial symmetry, caused by penetration of turbulent vibrations in the current-conducting part of the flow. All this produces an increase in the field strength along the transition segment and an increase in the thermal flux to the channel walls, now determined not only by radiation, but also by convective heat exchange. The length of the transition segment in the presence of an electric arc amounts to only 5-10 calibers, while, in the case of ordinary gas or liquid flow, it reaches an extent measured in tens of calibers.

Along the segment of well-developed flow, the electric field strength remains longitudinally constant, while the arc assumes a complex structure, which varies in time and space. However, as will be shown below, arc deflections toward the periphery remain within a radius much smaller than the channel radius.

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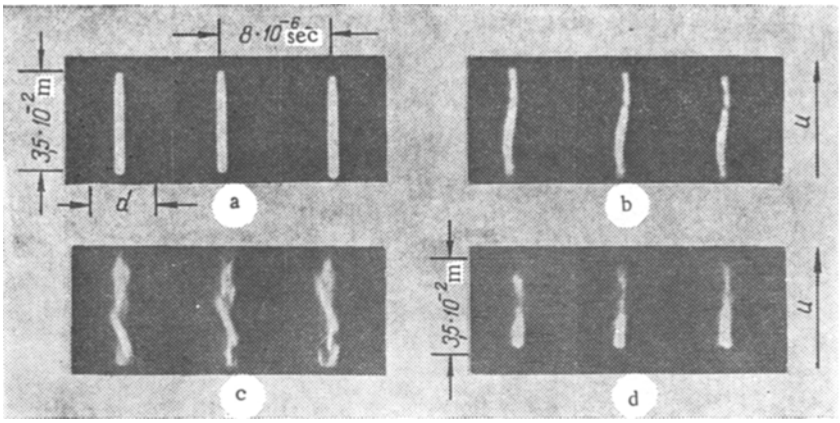

Fig. 1. Variation in the shape of an electric arc with longitudinal blowing along the channel (photographs taken with an SFR camera): $d = 1.5\cdot10^{-2}$ m, I = 80-100 A; and $Re = 10^4$. Air: a) $\bar{z} = z/d = 4$; b) 9; c) 18; argon; d) $\bar{z} = 18$.

The above characteristic features of gas flow development in a channel with arc discharge have been confirmed by the result of high-speed photography (Fig. 1). In a plasmotron incorporating a sectionalized interelectrode insert, a quartz tube of the same diameter and a length of $3.5\cdot10^{-2}$ m was inserted at various distances from the cathode. The arc in the tube was photographed on film by using an SFR or SKS camera. The experiments were performed in air and argon. The arc behavior at the initial and the transition segments is qualitatively the same for both gases. In the turbulent segment (Fig. 1c), the arc in air has a complex three-dimensional structure. It is characterized by a single or several brightly luminous current-conducting channels with rare short-lived discontinuities. A more uniform structure of the brightly luminous parts of the arc, which are separated from each other by markedly less intensive parts, is characteristic for argon (Fig. 1d). The development of nonuniform structures is not contemplated here. Within the segment with well-developed turbulence, an arc in argon seems to vibrate with a frequency of the order of 1 kHz, which is evident with great clarity from changes in the arc luminescence in photographs taken with an SKS camera with a time resolution of $\sim10^{-4}$ sec.

Within the segment with well-developed turbulence, the heat exchange in the current-conducting part of the arc is determined by turbulent thermal conductivity. The model by means of which the volt—ampere characteristic can be calculated with sufficiently high reliability is given below. For the described segment the thermal flux to the channel wall is composed of the convective thermal flux $Q_c$, determined by turbulent heat transfer, and the radiative thermal flux $Q_r$. The total thermal flux to the wall can be considered as an additive quantity, i.e., $Q = Q_c + Q_r$; this makes it possible to determine fairly easily the convective component. Processing of experimental data has shown that convective heat exchange within the flow segment with well-developed turbulence comprising the arc is described with high accuracy by the equation for convective heat exchange in turbulent flow under ordinary conditions, i.e., the arc exerts virtually no influence.

Such behavior of convective heat exchange at the channel wall must naturally be determined by the entire flow structure. Let us determine the size of the luminous current-conducting zone or the boundary of deflection of the current-conducting part under the influence of turbulence during a time considerably longer than the characteristic time of vibratory motion. For this, we recorded by means of a prism spectrograph the radiation intensity distribution of the continuum at the wavelength $\lambda = 393$ nm along the channel radius. The radial distribution of radiation was recorded over a period of 8 sec (Fig. 2), while the characteristic time of vibratory motion was equal to $10^{-4}$-$10^{-5}$ sec. In the investigated range of arc currents and Reynolds numbers, the recorded deflection radius did not exceed $\bar{r} = 2r/d \leq 0.5$. The Reynolds numbers were determined with respect to the cold gas temperature at the plasmotron inlet. The obtained deflection value, i.e., the mean size of the arc's current-conducting zone, can be related to the characteristics of the flow with well-developed turbulence in the tube. Figure 3 shows the distributions along the tube radius of the dimensionless coefficient of turbulent viscosity $\varepsilon_t$ and of the coefficient of spatial correlation R(r) between

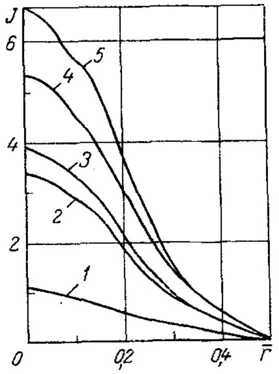

Fig. 2

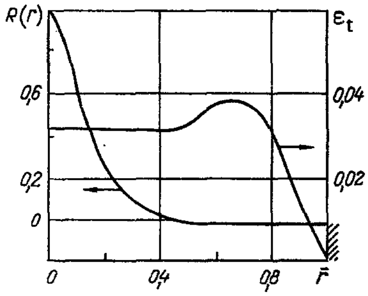

Fig. 3

Fig. 2. Radial distribution of the radiation intensity of an air arc in the continuum $\lambda = 393$ nm; $d = 2 \cdot 10^{-2}$ m. 1, 2, and 4) $Re = 3.2 \cdot 10^4$, $I = 50$, 100, 140 A; 3, 5) $Re = 7.45 \cdot 10^4$, $I = 100$, 140 A. J is given in relative units.

Fig. 3. Radial distribution of the turbulent viscosity coefficient $\varepsilon_t$ and of the coefficient of spatial correlation of longitudinal velocity vibrations R(r) for flow with well-developed turbulence in a tube.

longitudinal velocity vibrations. The integral of R(r) characterizes the turbulence structure; in this case, it constitutes a measure of existence of large scales [4].

Comparison between the curves shown in Figs. 2 and 3 suggests that the arc's current-conducting zone within the flow segment with well-developed turbulence lies in the axial region. The size of this zone in the radial direction is limited by the region comprising large-scale drifts, while it does not extend beyond the location of the maximum of the turbulent transport coefficient. Further, up to the channel wall, the gas flow structure is not much different from the structure of an ordinary turbulent flow. Thus, it can be stated that the mechanism of stabilization of an electric arc near the axis of a cylindrical channel is determined by the turbulent flow structure.

Of all the theoretical models of a turbulent electric arc, the simplest one, which also agrees well with experimental data, is the "channel" model, which has been proposed in [5]. It involves agreement between the theoretical and experimental volt—ampere characteristics in a wide range of turbulent arc parameters. The essence of the model consists in the following: The turbulent flow is subdivided into two regions — the core and the laminar sublayer. The turbulent thermal conductivity in the core is much higher than the molecular thermal conductivity, and the temperature and velocity gradients are assumed to be zero. The flow core constitutes the current-conducting region, which is at the constant temperature $T\sigma$. The temperature and velocity gradients are assumed to be constant in the laminar sublayer, while the sublayer itself constitutes a current-free region; the thickness of the sublayer is found from the criterion of its stability [6]. Radiative energy transport is neglected. For calculating the volt—ampere characteristics of a turbulent arc, we obtain in this case the simple analytic expression $Ed/\sqrt{Re} = f(I/d\sqrt{Re})$. Figure 4a and b shows the calculated and the experimental volt—ampere characteristics of the arc in argon [7] and air. The agreement is entirely satisfactory, especially if we consider the simplicity of the model used. The effect of the pressure p in the channel is accounted for with sufficient accuracy by introducing the factor $\sqrt[4]{p}$.

It is evident from the above experimental data (Figs. 1-3) that the "channel" model of a turbulent arc is quite different from the actual pattern of physical processes in an electric discharge chamber. This is also supported by the fact that the arc temperature $T_\sigma$ determined on the basis of the "channel" model for the parameters of the curves in Fig. 4 lies within the $6 \cdot 10^3 < T_\sigma \leq 8 \cdot 10^3$°K range. The radiation flux $Q_r$ from unit length of the arc for the 200-2000-nm spectrum section that is calculated on the basis of this model is much smaller than the flux measured in experiments. For instance, for air and for $d = 2 \cdot 10^{-2}$ m, $Re = 6.4 \cdot 10^4$, and $I = 140$ A, the obtained experimental strength and radiation flux values were equal to $E = 27.8$ V/cm and $Q_r = 60$ W/cm, respectively, while the $Q_r$ value calculated on the basis of the "channel" model was equal to 4 W/cm.

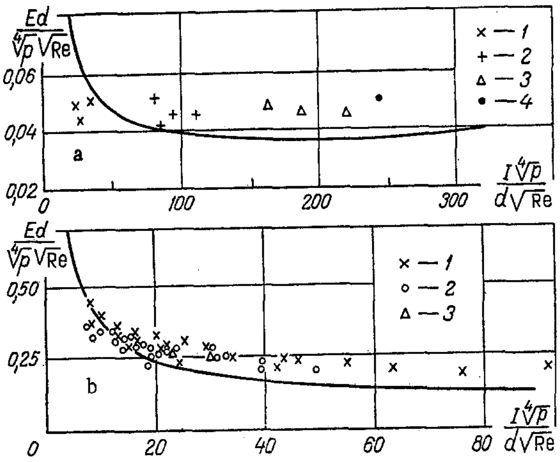

Fig. 4. Comparison between the theoretical (curves) and the experimental volt—ampere characteristics of discharge. a) Argon: 1) p = 0.1 MPa, d = $1 \cdot 10^{-2}$ m, I = 50 A; 2-4) p = 1.1 MPa, d = $0.7 \cdot 10^{-2}$ m, I = 100 A (2), 200 (3), 300 (4); b) air: I = 50-500 A, p = 0.1-2 MPa, d = $(1-3) \cdot 10^{-2}$ m, Re = $(3-7) \cdot 10^4$ (1), $1 \cdot 10^5$ (2), $5 \cdot 10^5$ (3).

The actual temperature can be estimated with respect to experimental data. If a rectangular temperature profile is assigned, we determined the mean diameter of the current zone $d_{cu}$ and the temperature from the conditions $I = \frac{\pi}{4} d_{cu}^2 \sigma E$ and $Q_r = \frac{\pi}{4} d_{cu}^2 U$ with respect to the known temperature dependences of the conductivity coefficient σ and the volumetric radiation coefficient U (for 200-2000 nm) by using the method of excessive approximations. For the above conditions, such an estimate yields $T_\sigma$ = 12,000°K and $d_{cu} = 0.183\, d/2$. It is evident that the value of $d_{cu}$ is close to the dimensions of optical nonuniformities (see Fig. 1). It should also be noted that the characteristic dimension of turbulent drifts for the tube, defined as $L = \int_0^{d/2} R(r)\,dr$ [4], amounts to 0.14 d/2.

However, the agreement between the volt—ampere characteristics calculated on the basis of the "channel" model and those obtained experimentally is not a random coincidence; it rather reflects the physics of the process. It was shown in [5] that, in the case of predominant turbulent thermal conductivity, the dimensions of the conduction zone do not affect the volt—ampere characteristic of the discharge. It is possible that heat exchange between turbulent current structures and the nonconducting region is determined by the thermal resistance of a thin layer, similar to the viscous sublayer at the wall, in which the mechanism of molecular thermal conductivity predominates.

On the whole, all the above data provide an idea of a turbulent arc that is possibly rather phenomenological in character, but it could serve as a basis for actual estimates of the complex processes of interaction between electric-arc discharge and a turbulent gas flow.

## NOTATION

$Q_c$, convective thermal flux to the channel wall; $Q_r$, radiative thermal flux from unit length of the arc; Q, total thermal flux; r, radial coordinate; d, diameter of plasmotron channel; $\varepsilon_t$, dimensionless coefficient of turbulent viscosity; R(r), coefficient of spatial correlation between longitudinal velocity vibrations; T, temperature; σ, electrical conductivity coefficient; E, field strength; I, arc current; Re, Reynolds number; u, longitudinal flow velocity; p, pressure in the channel; U, volumetric radiation coefficient; L, characteristic dimension of turbulent drift; $d_{cu}$, characteristic diameter of current filaments within the turbulent segment; J, radiation intensity.

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# OPTOSPECTROSCOPIC STUDIES OF THE CATHODIC JET OF A LAMINAR PLASMATRON

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The structure and temperature field of a cathodic jet near the external surface of the nozzle in a laminar plasmatron are studied.

Plasmatrons with a laminar flow in highly heated gas are used in plasma technology, in particular, in gas-thermal hardening of machine parts and mechanisms [1, 2]. They intensively heat and accelerate powder particles and thereby ensure that the powder is used efficiently [3]. As is well known, plasma atomizers in which the powder is injected at the cutoff of the nozzle have the longest lifetime. Because of the low plasma temperature in the zone of injection of the powder (7000-10,000°K), however, in such atomizers the efficiency of heating is several times lower than when the atomized material is injected into the nozzle directly near the cathode [4-6]. For this reason, a promising direction of development of long-lifetime atomizers, which at the same time heat particles to high temperatures, is to use plasmatrons with a short distance between the cathode and the exterior surface of the nozzle and to inject powder onto the nozzle cutoff.

In this work, employing optospectroscopic methods we studied the structure and temperature field of the plasma flow in a nitrogen atmosphere near the exterior surface of the nozzle at a distance of one unit from the cathode (Fig. 1). The working conditions of the discharge are: $1 = 200$-$500$ A, $U = 33$ V, and $G = 0.003$-$0.077$ g/sec. The structure of the flow was observed both visually and with the help of a motion picture film using an SKS-1M camera.

The plasma formation under study consists of a high-intensity conical, cathodic jet emanating from the nozzle with two symmetrically positioned expanding jets with a transverse size in the zone of contact with the anode of ~1 mm lying next to it. Under optimal conditions, which are achieved primarily by adjusting the gas flow, the electrode spots assume stationary positions on the surface of the anode within several tens of seconds. Then a jumplike change occurs in their spatial position with the symmetry mentioned above preserved. As the duration of the operation of the plasmatron increases the residence time of the spots at one location gradually decreases. Reliable observation of the spatial position of the cathodic and anodic jets was facilitated by their different color, which is determined by the different composition of the plasma.

Motion-picture photography of the plasma formation indicates that the stationariness of the plasma depends substantially on the geometry of the discharge chamber and the working conditions of the generator, and especially on the flow rate of the gas. The probability of transverse displacements of the cathodic jet increases appreciably with the diameter of the nozzle cutoff at a distance $L > 10$ mm. With the help of the SKS pictures, obtained with continuous photographic scanning, we estimated the velocity of the anodic plasma jets. For zones lying quite far away from the nozzles ($l > 20$ mm) it falls in the range 5-20 m/sec. We could not determine by an analogous method the velocity of the cathodic jet because the amplitude of the pulsations in the brightness of the jet was too low.

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