# ELECTRIC ARC IN A SUBMERGED GAS JET

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The results of photographic studies of the behavior of an electric arc in a submerged gas jet, using both regular photography and still and cine shadow photography, are presented. The interaction of the arc with the turbulent portion of the jet and the development of disturbances in the arc and the thermal layer around the arc dependent on initial jet velocity are noted. Experimentally obtained values for extent of the arc laminar zone, radius of arc thermal layer, and electric field intensity are compared with calculated values.

In recent studies [1-2] devoted to investigation of the characteristics of an electric arc passing longitudinally through a jet it has been shown that the turbulence of the gas flow has a strong effect on the local characteristics of the arc.*

However, the conclusions were based on the study of integral characteristics, with no detailed examination of the process of interaction between arc and turbulent gas layer, nor of the causes conditioning the appearance of instability in the arc column (pinch).

Conducting proper studies under real laboratory conditions is complicated by the presence of channel walls. Therefore, studies were made of the properties and behavior of an arc burning in a free jet. In [3] it was shown that, generally speaking, the arc stability is determined by the level of turbulence in the gas flow. To obtain a low turbulence free jet, a special apparatus was constructed, which permitted attainment of a submerged gas jet with turbulence level $\varepsilon \sim 0.5$-4% in the velocity range v = 10-300 m/sec. The arc was ignited along the jet axis.

*G. Frind, "Electric arcs in turbulent flows, I," ARL, pp. 64-148 (1964).

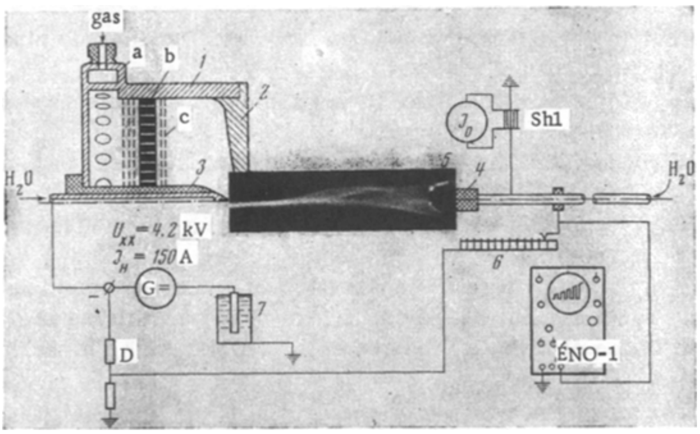


Fig. 1

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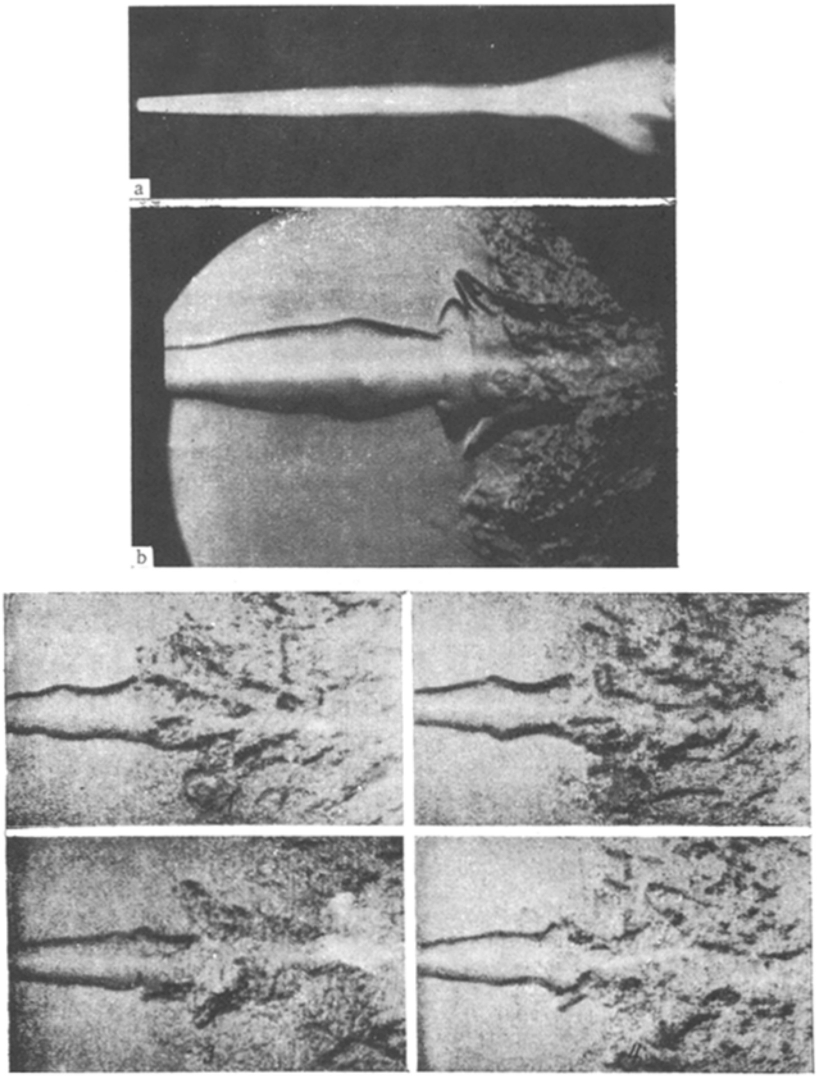

Fig. 2

1. A scheme of the apparatus, with which all experiments described below were conducted, is shown in Fig. 1. It consists of an antechamber 1 with removable nozzle 2, mounted on the axis of a cathode chamber 3, a movable anode 4 with insulation coating 5, coordinator 6, and water rheostat 7.

The antechamber was constructed with consideration of the requirements applicable to aerodynamic channels, and consists of an input collector a, ensuring uniformity of gas input into the chamber, a honeycomb b with thickness 20 mm and orifice diameter 3 mm, five screens c with mess dimensions $0.5 \times 0.2$, and removable output nozzle 2, constructed with a Vitoshinski curve. The chamber diameter is 186 mm, while output nozzle diameter for all experiments described below was 30 mm.

On the axis of the chamber is located a special type profiled water-cooled copper cathode with a zirconium wire of $d = 2$ mm pressed into its face. The cathode was located at a depth within the chamber (from the nozzle end) of 15 mm.

The special form and location of the cathode ensure minimum disturbance of the current flow by the central body, which in this case is the cathode.

Velocity profiles and turbulence levels were measured with a "Diza" system thermoanemometer, with a gold-plated tungsten filament, with $d = 5$ mm, $l = 2$ mm. The error in velocity measurement was 2-3% in the range 11-60 m/sec, and 4-6% in the range 60-120 m/sec.

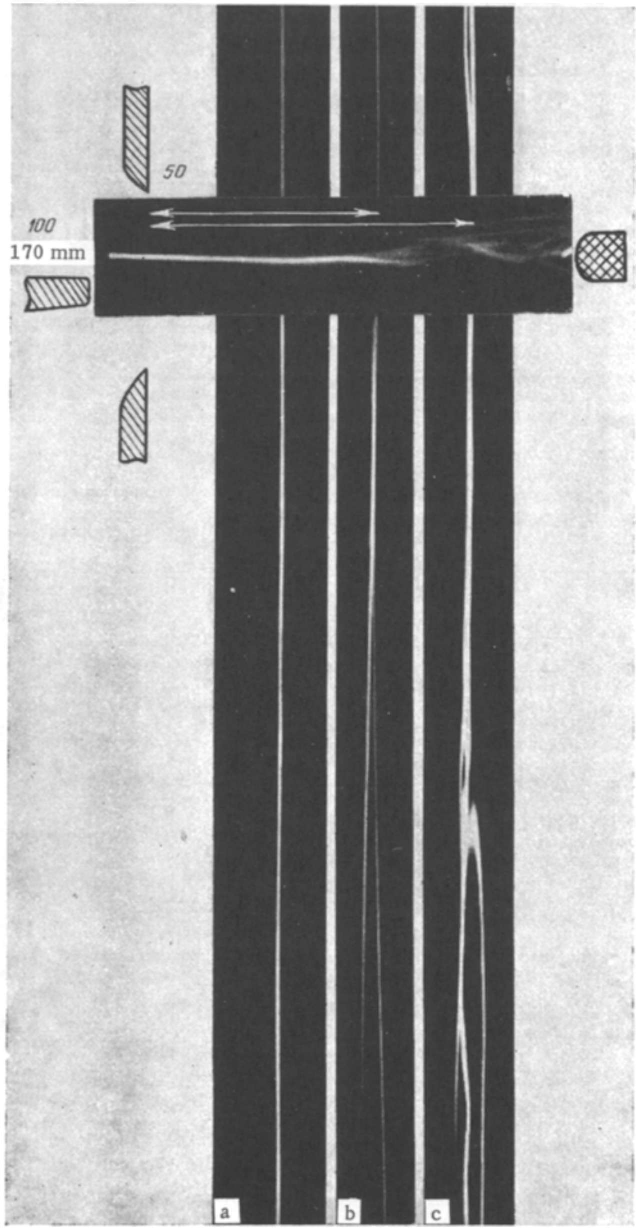


Fig. 3

Results of measurements showed that the turbulence level on the jet axis (in the nucleus) did not exceed 4% (minimum 0.3%), and the velocity profiles closely coincided with data from calculations conducted by the method of [4,5]. The coincidence of the calculated profiles with those measured permitted the use of the well-known relationships of [4,5] for determination of the position of the nucleus boundaries in further work.

The movable anode 4 was constructed of copper and cooled by water. The anode shape was chosen to ensure minimum disturbance of flow. The working surface of the anode, over which the anode spot moves, has an area of 15 $mm^2$.

Arc ignition was accomplished by bringing the electrodes into contact, with subsequent withdrawal of the anode with the aid of a spring drive mechanism.

It was possible to measure gas flow rate (with the aid of measurement nozzles) and arc current and voltage, while oscillographs could be made of voltage both during operation and while extending the arc at ignition. During anode withdrawal, the voltage was applied to the oscilloscope through a special coordinator, which permitted obtaining data on electric field intensity.

The basic task of the study was to investigate the behavior of an arc in a submerged jet, its stability relative to the flow axis, and the causes conditioning instability.

Cine photography using an SKS-IM apparatus, high-speed photography of transverse arc oscillations with an SFR streak camera in photoscanner mode, conventional photography, and still and cine shadow photography were employed.

For shadow photography the light source used was an ISh-5 lamp with flash energy of about 4 J, and flash duration 5 μsec. For cine shadow photography an LG-75 gas laser was used as the light source, at a speed of 4000 frames/sec. An SS-4 light filter was used in the conventional photography, while an interference filter was employed for cine shadow photography.

A conventional photograph, a shadow photograph, and consecutive cine frames are presented in Fig. 2a, b, c.

2. The investigations conducted proved that stable arc burning is possible in a free low-turbulence jet. Streak camera pictures, taken at I = 100 A, G = 60 Hz at various distances (s = 50, 100, 170 mm, measured from nozzle orifice), along the length of the arc, show that in the initial zone (Fig. 3a) departure of the arc from the stream axis is undetectable over a frame rate range of 4000-200 frames/sec. For a decrease in flow, arc instability increases, as is shown in the following streak photos (Fig. 3b, c).

Shadow photographs permit the determination of a certain boundary in the thermal layer around the arc (the arc layer), namely, the region where a sharp change in density of the medium occurs.

An estimation of the position of the maximum density gradient by enthalpy profiles using a fourth order approximating polynomial [2] and a numerical calculation method [5,6] shows that this point is located sufficiently near (with error no greater than 10%) to the boundary of the arc layer, where a transition to the enthalpy of the surrounding medium occurs. For relatively low flow velocities (up to about 20 m/sec) the boundary of the arc layer over some initial portion is a smooth monotonic curve.

With an increase in velocity, the boundary begins to undergo periodic, evidently nearly axiosymmetric, disturbances, which then lose their symmetry, and upon which finer disturbances are superposed, penetrating ever deeper into the arc layer.

High-speed cine photography shows that aside from the arc-layer boundary disturbances, there occur periodic local disturbances of the arc column, which traverse the length of the arc in the direction of current flow. These disturbances also become noticable only at some threshold velocity. Nevertheless, the arc column for some length in the middle remains linear.

In all cases, at some distance from the nozzle there occurs an abrupt intermixture of the arc-layer gas mass with the surrounding medium. This process, as high-speed cine photography shows, has an "explosive" character and calls to mind illustrations of Reynolds' classic experiments with a colored jet in a liquid stream.

This last phenomenon is undoubtedly the consequence of interaction of the arc layer with the turbulent region of the jet. This is also supported by the fact that the point at which arc-layer disintegration begins coincides, approximately, with the point of intersection of the theoretical flow-nucleus boundary with the experimental boundary of the arc layer. At some greater distance from the origin the arc column begins to undergo chaotic oscillations.

With an increase in velocity, these points, i.e., the point of arc-layer disintegration, and the point at which turbulent oscillations of the arc begin, approach each other. This is evident from Fig. 4, wherein values are presented for $x_0'$ and $x_0$, the distances from nozzle orifice to the indicated points (curves 1 and 2 are experimental values of $x_0'$ and $x_0$, respectively; curve 3 is the theoretical value of $x_0$).

It is interesting to note that $x_0$, the length over which a straight arc column exists, while increasing at low velocities, and maintaining an equal distance from $x_0'$, begins to decrease at higher velocities. This is evidently conditioned by the formation and development of the disturbances in the arc-layer boundary mentioned above, which gradually begin to affect the current bearing region of the arc layer, the arc column itself.

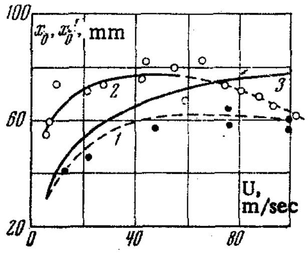


Fig. 4

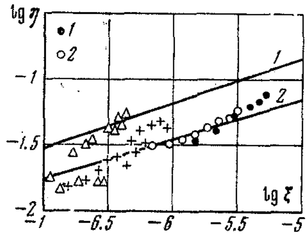


Fig. 5

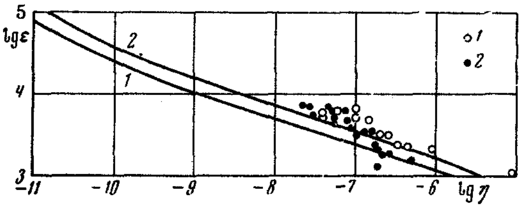


Fig. 6

A comparison was made of theoretically and experimentally determined positions of the arc-layer boundary, which is presented in Fig. 5. Curve 1 is a solution for the arc-layer boundary obtained by the integral method of [2]

$$\eta = 7.2\xi^{0.339} \tag{2.1}$$

while curve 2 is an approximation of the line of greatest density gradient, calculated by the numerical method of [5]

$$\eta = 2.82\,\xi^{0.315}$$

$$\eta = \frac{2\pi\sigma}{I}\sqrt{\frac{\lambda_0 h_0 \sigma_0}{c_{p_0}}}, \quad \xi = \frac{z h_0 \sigma_0 \lambda_0^2 4\pi^2}{I^2 \rho_\infty u_\infty c_{p_0}^2} \tag{2.2}$$

Here $\lambda_0$, $h_0$, $c_{p_0}$ are characteristic values of thermal conductivity, enthalpy, and heat capacity (taken equal to the values for a free flow); $\sigma_0$ is the characteristic value for electrical conductivity (taken as 436 mho/m [2,6]); $\rho_\infty$, $u_\infty$ are the density and velocity of a free flow; I is current strength; z is the axial coordinate measured from the electrode located within the nozzle; and $\delta$ is the radial dimension of the arc layer. Points 1, 2, +, Δ correspond to velocity values of U = 12.0, 24.8, 62.0, 124.0 m/sec.

It is evident that the latter formula agrees well with experimental data. The deviation of the points at higher velocities is produced by the presence of the wavelike disturbances in the arc-layer boundary described above. Basically, the theoretical dependence passes between the high and low points of the experimentally determined arc-layer boundary.

To theoretically determine the point of disintegration of the arc layer, the points of intersection of the curves of Eq. (2.2) at various velocities with the boundary of the flow nucleus were found, the latter being given by the formula of [4]

$$y = -\frac{a}{0.67}(z - z_0) + R \tag{2.3}$$

where $z_0$ is the depth of the electrode within the nozzle ($z_0$ = 15 mm), R is nozzle radius (R = 15 mm), and $a$ is an experimental constant ($a$ = 0.07).

The results of the calculation, presented in Fig. 4, show good agreement of theory and experiment at low flow velocities. At high flow velocities, the experimental data lie below the theoretical, which is evidently a consequence of disturbances in the arc layer, which lead to earlier interaction with the turbulent flow region.

Experimental data on electric field intensity were compared with theoretical values for an arc in an infinite air stream. The results are presented in Fig. 6, where in addition to the results of this study, there are presented measurements of field intensity in the initial portion of a cylindrical channel [6, 7] where the effect of the walls may be neglected (curve 1 was obtained by numerical methods, curve 2 by integral method; the points 1 are for an arc in a channel, points 2, for an arc in a jet). The experimental data agree well with both the numerical and integral solutions.

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