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INVESTIGATION OF THE INSTABILITY OF AN ARC DISCHARGE IN AN AIR FLOW

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Using an automated complex of spectral apparatuses that allow one to determine local profiles of averaged temperature and its oscillations in a dc arc-discharge column, we investigated the temperature instability of the arc plasma in a laminar air flow. We show that the character of oscillations corresponds to the model of thermal destabilization of discharge.

At the present time, electric arc discharges are finding use in various technological processes. One of the most widely used arc apparatuses is the vortex plasmatron, which is designed to heat gases to high temperatures. An arc burns between a rod cathode in the cavity of a sectioned channel and is shorted to the electrode in its final part (Fig. 1). The gas is supplied with twisting in the cathode region and then flows along the anode, while being heated by the electric arc. Due to vortical motion, the cold layers of the gas are displaced to the anode wall, insulating the arc electrically from the anode over the whole length of the arc column, except for its final part, which contacts the electrode. The heated gas leaves the anode as a plasma jet, which has a number of uses.

The character of the jet flow is of considerable importance for application of a plasma jet. Mixing of the raw material with the plasma is better in a turbulent than in a laminar jet, but a turbulent jet is also intensely mixed with the environment. In this case the length of the jet is reduced, as is the time of the interaction of the material with the plasma. The character of flow in a jet is determined by the conditions of arc interaction with the gas flow in the plasmatron channel.

The process of flow turbulization by a heated arc is much more complex than in the case of cold flows. Transition to a turbulent regime in the plasmatron channel is determined not only by the critical value of the Reynolds number. The velocity and temperature of the gas depend on both its flow rate and the dimensions of the channel, as well as on the electric-arc power. Therefore, when the flow regime is determined, it is also necessary to take into account the criteria that characterize the processes of heat release in the arc and energy exchange between the arc and the gas. On the other hand, the character of the flow that blows the arc influences the conditions of heat exchange in the arc column and the behavior of the column itself in the channel. Over the initial portion of the discharge the column is blown by a laminar flow and occupies a stable position along the discharge axis. Farther downstream the wall boundary layer grows, and after its intersection with the arc column the latter begins to oscillate intensely and to bend [1]. The flow in the interior of stable arc discharges is predominantly laminar, because of the high viscosity of plasma. However, the arc discharge has its own different sources of destabilization that can cause turbulization and change the conditions of heat exchange.

The problem of heated gas turbulization in the plasmatron channel was considered in [1]. Some data on thermal stabilization in the plasma of arc discharges blown by argon and helium are presented in [2-5]. A very important process gas for obtaining plasma is air from the viewpoint of both the practical application of air plasma and for extending the range of the media investigated to elucidate the nature of thermal destabilization. Therefore we carried out investigations of an electric arc in the channel of a vortex plasmatron with blowing by an air flow

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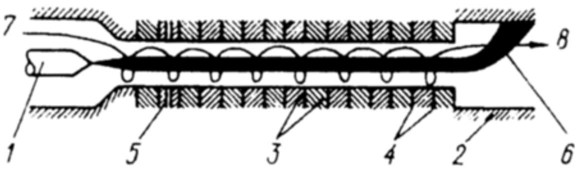

Fig. 1. Schematic diagram of an experimental dc vortex plasmatron: 1) thermal emission rod cathode, 2) cylindrical anode, 3) diaphragms, 4) high-temperature insulation, 5) measuring window transparent to arc radiation, 6) electric arc, 7) supply of process gas, 8) outflow of plasma jet.

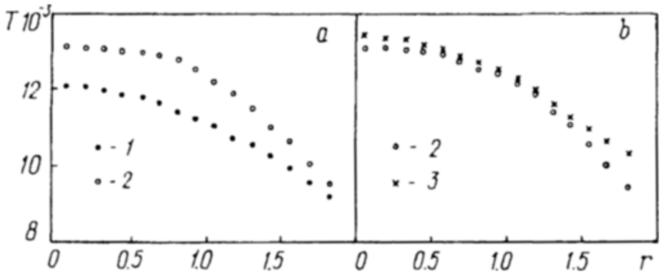

Fig. 2. Averaged temperature profiles versus the gas flow rate (a) and current (b), $d = 8$ mm: 1) $G = 0.2$ g/sec; $I = 76$ A; 2) 1.0 and 80, 3) 1.0 and 117. T, K; r, mm.

and of temperature destabilization in the air arc column. Below we present some results of the investigation of temperature instability in an arc blown by a laminar air flow.

To investigate temperature instability in the plasmatron channel, the windows in it were made transparent to radiation. We took pictures of the oscillations of the arc column in sections located opposite the windows using continuous sweep photography. Time resolution attained 10^{-5} sec. Spectral measurements were made by an automated spectrometer on the basis of a diffraction monochromator with a 1200 line/mm grating. The working range of the spectrometer was 200–1200 nm, and the maximum rate of spectrum scanning was 80 nm/sec. The spectrum was recorded by a photomultiplier (PM). The spatial profiles of the radiation intensity of stable arc columns were recorded by a scanning device based on a stepper motor with a scanning step of 0.125 mm along the arc column diameter. Each spatial distribution was represented by 64 readings and was recorded four times at two or three points over the spectrum. Optical spectra were recorded in a period of 3 sec. The number of points was 2048. Oscillations of the radiation intensity were recorded by an SK4-58 spectrum analyzer in the 0.4–600 kHz frequency range and accumulated in an electronic computer.

Using special programs, we calculated the averaged value of radiation intensity and the mean-square value of its oscillations at each point of the space profile. Then, taking the inverse Abel transform we calculated the averaged and fluctuational characteristics of the radiation intensity at points of local profiles. The averaged temperature on the arc column axis was calculated from the relative intensity of the NI 847.7 nm and OI 882 nm lines. The decrease in temperature over the arc column radius was determined by measuring the absolute intensity of these lines. Conversion of the radiation intensity oscillations into temperature fluctuations was performed at each point of the profile from the temperature dependence of the line radiation intensity. Thus, we found the local profiles of the averaged temperature and of its fluctuations depending on the arc burning regime.

Most characteristic for thermal destabilization of a discharge is the initial portion of the arc blown by a laminar gas flow, where the arc column preserves its stable position, as established by using high-speed photography. The influence of the gas flow rate and the current on the profiles of the averaged temperature for this portion is shown in Fig. 2. It is seen from the figure that an increase in the gas flow rate leads to a marked increase in temperature on the arc column axis and to a steeper decrease in temperature towards its periphery. An increase in the current also causes a rise in the axial temperature, though not as substantial as in the case of a

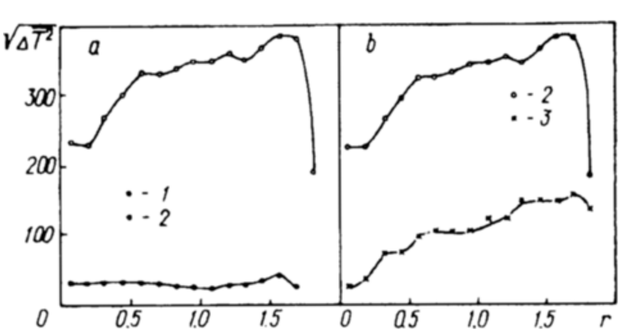

Fig. 3. Profiles of temperature fluctuations versus the gas flow rate (a) and current (b), $d = 8$ mm. The notation is the same as in Fig. 2.

change in the gas flow rate. As the current was increased, we also observed a certain expansion of the electrically conducting zone of the arc and a flattening of the temperature profile within its limits.

Figure 3 presents the profiles of temperature fluctuations with changes in the gas flow rate and arc current. An increase in the gas flow rate causes a substantial increase in the intensity of temperature fluctuations (Fig. 3a), while a current increase leads, conversely, to a certain reduction of instability. In the indicated regimes of arc burning we observed an increase in the level of fluctuations in the direction of the discharge periphery, though at the very edge of the region in which the temperature changed in all of the cases we noted a tendency towards a decrease in the intensity of instability. This decrease in the level of destabilization at the periphery of the column implies that fluctuations are excited within the limits of a discharge and do not penetrate it from without. It is necessary, however, to elucidate the reason for destabilization.

Perturbations can be caused both by aerodynamic factors due to a sharp change in the flow velocity at the periphery of the discharge and by thermal factors. Comparison with known data on the temperature instability profiles in a helium arc point to a thermal source of instability [4, 5]. For an air arc this can be verified on the basis of the mechanism of thermal turbulization. The basis behind the model is the strengthening of random temperature perturbations by means of additional heating of plasma flows in expanding local overheated zones by internal energy sources. Such a basic source of internal heat liberation in an electric arc discharge is Joule dissipation, though the process of energy transfer also exerts a certain effect. An additional supply of energy to an accelerating flow at subsonic velocities causes an increase of its kinetic energy due to the "thermal nozzle" effect, leading to an increase in plasma deceleration in an expanding local region. As a result, when the expansion of an accidentatly heated "bubble" stops, the local temperature may turn out to be substantially higher than its original level. In the presence of temperature gradients typical of arc discharges, the symmetry of the expanding overheated region is violated, and energy transfer in the direction of the decreasing temperature appears.

The presence of such "turbulent" energy transfer can be used to check the correspondence between a temperature instability detected experimentally in a discharge and the condition of thermal destabilization. The acceleration of gas due to the enthalpy of superheating Δh occurs by means of the conversion of the thermal energy of the flow into the kinetic energy of its directed motion. In this case the divergence of the turbulent heat flux should be negative: $q_t \approx \rho h\sqrt{2\Delta h} < 0$. The value of $q_t(r)$ can be calculated from the experimentally measured profiles of averaged temperature using the temperature dependence of the properties of an air plasma [6, 7]. If the regions of the peaks of temperature fluctuations and of the decrease of $q_t(r)$ coincide, this indicates thermal excitation of the instability observed. The difficulties in conducting such an analysis are associated with the fact that the value of Δh cannot be determined experimentally from the level of temperature fluctuations, as energy transfer is induced by relatively small (compared to the peak ones) enthalpy differences as a result of deformation of expanding local regions in the gradient field. But since we need to know only the character of change in the turbulent heat flux, rather than its absolute value, we may calculate the value of $\Delta h(r)$ from the averaged temperature profile and temperature dependence $h(T)$ using a certain constant rather small step over the radius.

A comparison of the profiles of $q_t(r)$ calculated by the above-indicated method for the initial laminar portion of the arc column at $I = 80$ A and two values of the gas flow rate, $G = 1.0$ g/sec and 4.0 g/sec, is presented in Fig.

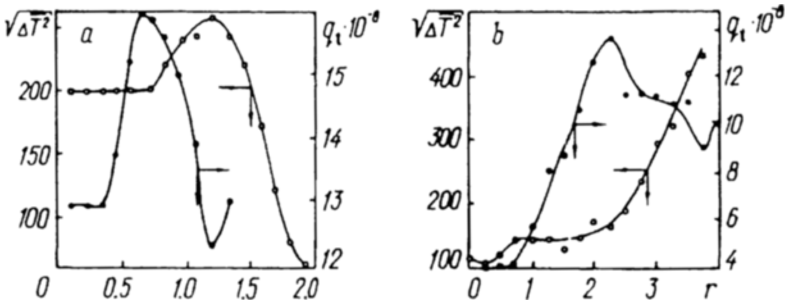

Fig. 4. Comparison of the profiles of temperature instability and of a turbulent heat flux, $d = 8$ mm, $I = 80$ A: a) $G = 1$ g/sec; b) 4.0 g/sec. q_t, W/m^2.

3. We can see that, in contrast to Fig. 4, an increase in the gas flow rate above $G = 1.0$ g/sec led in this case not to a further increase in the instability level, but to its decrease. A second interesting fact is the displacement of the maximum of temperature fluctuations closer to the discharge axis with an increase in the gas flow rate. In this case the periphery of the arc column displayed a distinct decrease in instability. This indicates that the gas flow rate does not govern the process of temperature destabilization. Correspondingly, the aerodynamic character of the excitation of fluctuations in an air arc does not receive a logical confirmation on the basis of this experimental evidence. In contract to this, the thermal nature of destabilization is supported by experiments. At $G = 1.0$ g/sec, the increase in instability for $r > 1.0$ mm coincides with the region of a decrease in $q_t(r)$. The simultaneous increase in the level of fluctuations and in $q_t(r)$, when $r < 1.0$ mm, is not at variance with the thermal character of destabilization, since in this region the instability propagating from the periphery zone in the direction of the discharge axis is suppressed. In this case there are no sources of plasma perturbation in the axial region. When $G = 4.0$ g/sec, the regions of the growth of temperature fluctuations and decrease in $q_t(r)$ also coincide. But here we observe the presence of a kind of instability source also in the vicinity of the discharge axis, as shown by the character of both curves.

Thus, investigation of the temperature instability in a laminar air arc indicates thermal destabilization of discharge.

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REFERENCES

1. M. F. Zhukov, A. S. Koroteev, and B. A. Uryukov, Applied Dynamics of a Thermal Plasma [in Russian], Novosibirsk (1975).
2. Y. K. Chien and D. M. Benenson, IEEE Trans. Plasma Sci., **PS-8**, No. 4, 411-417 (1980).
3. T. V. Laktyushina, G. P. Lizunkov, and O. I. Yas'ko, in: Proc. ISPC-10, Bochum, Germany, 4-9 August 1991, Vol. 1 (1991), pp. 1-6.
4. T. V. Laktyushina, G. P. Lizunkov, and O. I. Yas'ko, Inzh.-Fiz. Zh., **62**, No. 5, 691-700 (1992).
5. T. V. Laktyushina, G. P. Lizunkov, V. D. Shimanovich, and O. I. Yas'ko, in: High Temp. Chem. Processes, Vol. 2 (1993), pp. 167-178.
6. A. S. Predvoditelev, E. V. Stupochenko, E. V. Samuilov, I. A. Stakhanov, A. S. Pleshanov, and I. B. Rozhdestvenskii, Tables of Thermodynamic Functions of Air for Temperatures of from 6000 to 12,000 K and Pressures in the Range of 0.001 – 1000 atm [in Russian], Moscow (1957).
7. A. S. Predvoditelev, E. V. Stupochenko, A. S. Pleshanov, E. V. Samuilov, and I. B. Rozhdestvenskii, Tables of Thermodynamic Functions of Air for Temperatures of from 12,000 to 20,000 K and Pressures in the Range of 0.001 – 1000 atm [in Russian], Moscow (1959).