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CONCERNING THE MECHANISM OF THERMAL DESTABILIZATION OF AN ARC DISCHARGE

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We examine the destabilization of arc discharges blown by a stream of a heated gas in the channel of a vortex plasmatron. A multitude of destabilizing factors of hydrodynamic and thermal origin are noted. We suggest a model of thermal destabilization due to sources of local heat generation. Experimental data on temperature fluctuations in the columns of argon and helium arcs support the model.

Electric arc discharges in the channel of a vortex plasmatron blown by a longitudinally vortex flow of a heated gas are a very complex object of investigation. Theoretical analysis of this phenomenon is difficult not only because of the complexity of interrelated electromagnetic and gas-dynamic processes, but also because of discharge instability. A significant source of destabilization is the gas flow. Experiments show that the instability develops downstream. Over the initial portion the arc column occupies a rather stable position along the axis of the discharge channel, but after the intersection of the growing boundary layer with the column the latter is destabilized, experiencing random oscillations and bending. The electric field strength averaged along the axis increases substantially in this case [1].

Investigation of temperature fluctuations inside an argon arc column shows different radial distributions in laminar and turbulent flows [2]. These results are contradictory if they are considered from the viewpoint of the penetration of hydrodynamic instability from the external flow into the interior of the arc column.

When an arc is blown by a laminar flow, the level of instability turns out to be maximal at the column periphery; it gradually decreases in the direction of the axis (see Fig. 1a). Such a distribution of fluctuations is typical for a gradual decay of the external turbulence penetrating into the arc. The turbulence is suppressed by the high viscosity of the arc plasma. But the laminar external flow does not contain turbulent perturbations. Consequently, the instability is generated in the external zone of the arc due to a sharp change in the flow velocity or temperature of the plasma.

If the instability in the arc column had been caused by penetrating external turbulence, the character of the radial distribution of temperature fluctuations in the arc blown by a turbulent flow would be the same as in a laminar arc, but their level would be higher due to the superposition of the external turbulence. However, in this case the maximum temperature instability is observed closer to the axis, while there is a drop in fluctuations in the outer zone (Fig. 1b). This result allows the assumption that the temperature fluctuations have not a hydrodynamic but rather a thermal nature, since the peak of instability is located outside the region of the maximum change in flow velocity. Penetration of external turbulence into the column apparently does not occur, because of the high viscosity of precisely the outer zone of the arc column.

The data of [3] also testify to the suppression of hydrodynamic turbulence in an electric arc. Moreover, the development of oscillations of an arc column as a whole and its deformation during arc burning in a turbulent flow show that a discharge behaves as a foreign body and not as a part of the gas flow. The thermal nature of the excitation of temperature fluctuations inside an arc discharge is also evidenced by an increase in instability at the center of a helium discharge (Fig. 1b) [4].

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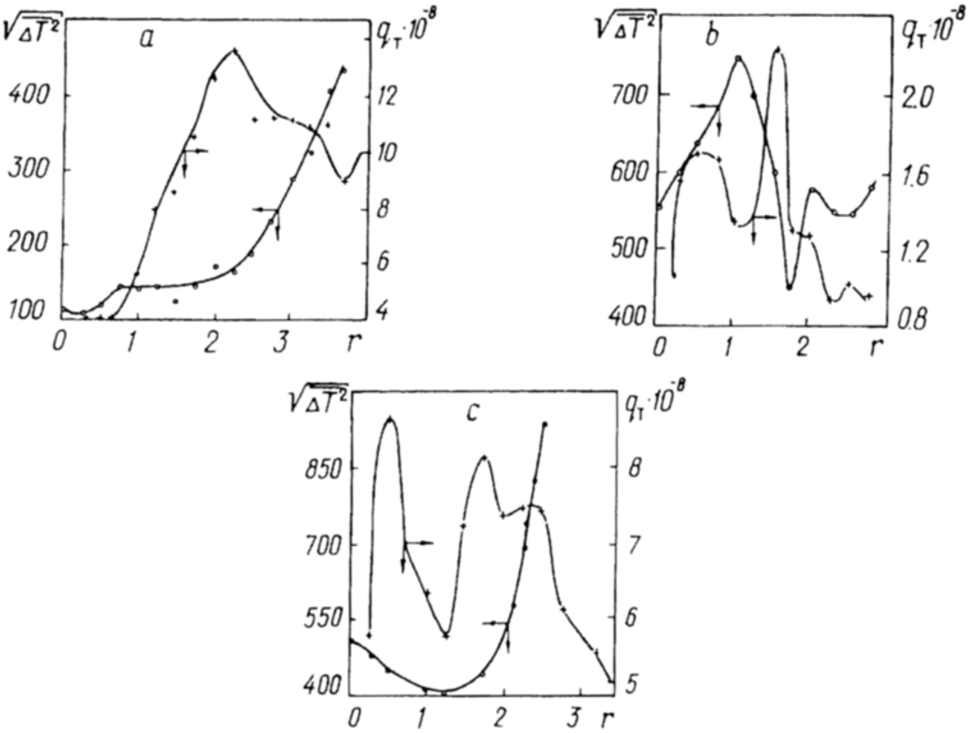

Fig. 1. Comparison of the profiles of temperature instability and turbulent heat flux a) in a laminar argon arc: $G = 0.1$ g/sec, $I = 65$ A, $d_r = 10$ mm; b) in an arc blown by a turbulent argon flow: $G = 7.7$ g/sec; $I = 65$ A; $d = 10$ mm; c) in an arc blown by a laminar helium flow: $G = 0.2$ g/sec; $I = 160$ A; $d = 8$ mm. $(\overline{\Delta T^2})^{1/2}$ K; q_T, W/m^2; r, mm.

There are many sources of temperature destabilization in an electric arc discharge: pulsations of the voltage of a rectifier, excitation of fluctuations due to the negative differential resistance of the arc, perturbations by random shunting of a discharge in an outlet electrode, overheating and ionization instabilities of plasma. The question arises, however, of whether or not temperature fluctuations can cause turbulent flows of plasma in the interior of the arc. This requires a positive answer. Since in a gradient temperature field, turbulent flows create a specific energy transfer, it can be detected by the method of the correlations of the discharge characteristics from the arguments that reflect different forms of heat transfer. Such a correlation revealed the presence of a turbulent energy exchange precisely in a helium arc, in which a growth in temperature fluctuations in the central portion of the column was discovered [5].

Let us consider the mechanism underlying the generation of unstable plasma flows due to temperature perturbations. A fast temperature increase in a certain local region also causes an increase in plasma pressure at that point, which leads to expansion of an accidentally overheated "bubble." In the absence of additional heating of radial plasma flows, their maximum velocity will be $v < \sqrt{2\Delta h_0}$, where Δh_0 is the enthalpy of the initial local plasma overheating. But since the process of expansion proceeds in the zone of thermal energy liberation due to Joule dissipation, the "heat nozzle" effect comes into action, which causes additional acceleration of the subsonic flow during its heating. As a result, at the final stage of expansion the enthalpy of jet deceleration can be substantially higher than its initial value. This leads to the intensification of temperature instability.

In a gradient temperature field the expansion of an accidentally overheated local zone becomes asymmetric, and this leads to the intensification of energy transfer in the direction of decreasing temperature. Thus, specific energy transfer by the mechanism of thermal turbulence appears. Estimates show a high efficiency of this form of energy transfer, compared with other means.

As is seen from the described mechanism of plasma destabilization, thermal turbulence differs substantially in character from hydrodynamic turbulence. It is generated not by the kinetic energy of the directed motion of a stream, but rather by fluctuations of the plasma enthalpy. It is evident that this type of turbulization is also possible in an immovable medium, but its main condition is the possibility of additional heating of overheated local zones that have been expanded accidentally. Therefore, the most favorable media for the appearance of thermal instability are high-temperature objects with internal sources of heat generation, such as, flames, electric discharges, and thermonuclear reactors. However, in the absence of transformation of different forms of energy into thermal energy, the development of thermal instability is possible in objects with large drops of temperature and gas velocity, when local energy sources appear due to the divergence of heat fluxes (convective, conductive, radiative).

In order to verify the considered mechanism of thermal destabilization, it is possible, along with the mentioned method of the correlation of discharge characteristics, to resort to the condition that the thermal acceleration of plasma occurs during the transformation of the thermal energy of the flow into the kinetic energy of its directed motion, $q_T \approx \operatorname{div} \rho h\sqrt{2\Delta h_{ef}} < 0$. Using the experimental data on the radial distributions of the average plasma temperature and its fluctuations, as well as the temperature dependences of the plasma properties, we can calculate $q_T(r)$ and compare this profile with the distribution of temperature fluctuations $(\overline{\Delta T^2})^{1/2}(r)$. If temperature instability develops precisely due to the enhancement of random fluctuations by the means considered, a growth of temperature fluctuations should be observed in the region of the decreasing q_T.

The inconvenience of this method is the difficulty in determining the effective value Δh_{ef}. This value is much smaller than the one which can be found experimentally from temperature fluctuations, since energy transfer is determined only by the enthalpy drop that is caused by deformation of the expanding bubble. Fortunately, for the purpose considered it is not necessary to know the absolute value of Δh_{ef}, but only the character of its change along the radius. For this we can select a certain rather small step along the arc column radius and, using the profile of average temperature, calculate $\Delta h(r)$ and $q_T(r)$.

In Figs. 1a and 1b, $q_T(r)$ distributions obtained by the indicated method are compared with experimental profiles of the temperature fluctuations for an argon arc blown by laminar and turbulent flows, respectively, while Fig. 1c presents a similar comparison for a laminar helium arc. In a laminar argon arc, temperature fluctuations increase at the periphery of the column. It is precisely in this region that a decrease in q_T is observed. In a turbulent arc there is a large peak of fluctuations at the radius $r \approx 1$ mm, then a drop in instability, and a new increase in the external zone of the column. Correspondingly, the function $q_T(r)$ has falling portions in the region of both increases in $(\overline{\Delta T^2})^{1/2}(r)$. The irregularity in temperature fluctuations at the periphery of the column corresponds to small fluctuations of $q_T(r)$.

In a helium arc one also observes two descending portions of the function $q_T(r)$ corresponding to the central and peripheral peaks of temperature instability.

Thus, experimental data indicate the thermal character of the development of instability in an argon arc in correspondence with the model suggested.

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