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DEPENDENCE OF THERMAL DESTABILIZATION OF ELECTRIC-ARC PLASMA IN AN AIR FLOW ON DISCHARGE CONDITIONS

**V. N. Borisyuk, S. V. Goncharik,
L. E. Krat'ko, A. S. Olenovich,
L. P. Podenok, L. I. Sharakhovskii,
V. D. Shimanovich, and O. I. Yas'ko**

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The effect of the conditions of electric-arc burning in an air flow on the process of thermal destabilization is considered. The considerable role of heat-transfer processes in the development of instability in an arc-discharge column is shown.

The model of the development of thermal turbulence presupposes additional heating of the plasma in expanding local regions of the electric discharge that are randomly superheated. The main source of plasma heating is Joule dissipation. However, the processes of heat exchange through which heat can be supplied to the local zone and removed from it also have a substantial effect. The supply of energy encourages the development of thermal instability in subsonic plasma flows while its removal contributes to the suppression of random temperature pulsations. The processes of energy transport themselves are dependent on the arc conditions, which determine the intensity of Joule dissipation and heat fluxes due to various mechanisms.

A most important condition is the medium in which the electric discharge is initiated. The thermodynamic and transport properties of the plasma and hence the intensity of energy-exchange processes are dependent on the chemical composition of the medium. In the literature there are some data on processes of thermal destabilization in argon and helium arcs [1-3]. It is desirable to investigate this influence in the case of arc blowing by air flows, too, since air plasma is used extensively in various technological processes. Furthermore, air, unlike argon and helium, is a molecular gas with its own temperature dependence of plasma properties.

The temperature instability of an air arc was investigated on a plasmatron with a sectioned channel that consisted of individual isolated copper disks. The channel was located between the hafnium end cathode and the cylindrical copper anode. For measurement we could replace one of the disks at a certain distance from the cathode by a special section equipped with transparent slit windows. The diameter of the discharge channel was 8 mm; the current varied from 60 to 120 A. The flow rate of the air varied from 0.2 to 4 g/sec.

The temperature instability was investigated using an automated unit for spectral measurements. The equipment made it possible to measure the intensity of radiation with a time resolution of up to 10^{-5} sec. The image of the arc was scanned in steps of 0.125 mm over the column diameter. Special programs converted the intensity of radiation from the measured profile to the local one and the values of the average temperature and its root-mean-square deviation were determined. The temperature at the center of the column was measured by the relative intensity of spectral lines while the temperature profile was determined from the change in the absolute intensity of the lines along the radius. An improvement in accuracy was also attained by finding local equilibrium values of the temperature through measuring the electron concentration by H_α.

To eliminate errors in determining the level of temperature fluctuations due to oscillations of the arc column as a whole, the measurements were performed on the initial region of arc blowing at a distance of 36 mm from the

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Academic Scientific Complex "A. V. Luikov Institute of Heat and Mass Transfer of the Academy of Sciences of Belarus," Institute of Molecular and Atomic Physics of the Academy of Sciences of Belarus, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 70, No. 2, pp. 246-251, March-April, 1997. Original article submitted August 4, 1994.

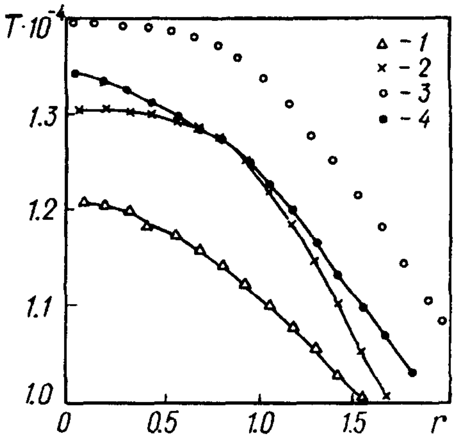


Fig. 1. Profiles of the average temperature in air-blown arc (d = 8 mm): 1) I = 76 A; G = 0.2 g/sec; 2) 80 and 1; 3) 80 and 4; 4) 117 and 1. T, K; r, mm.

cathode, where the column was free of pronounced oscillations. Stabilization of the position of the column was monitored by high-speed filming.

The influence of conductive energy transfer on processes of thermal destabilization of the air plasma in a local region was estimated by the ratio of the divergence of the conductive heat flux to the Joule dissipation intensity:

$$F_1 = -\frac{4\pi^2}{I^2\sigma r}\left(\int_0^R \sigma r dr\right)^2 d\frac{d}{dr}\left(r\lambda\frac{dT}{dr}\right), \tag{1}$$

where the expression $(4\pi^2/I^2)(\int_0^R \sigma r dr)^2$ is the reciprocal of the square of the electric-field strength E, which was assumed to be constant over the entire cross-section of the arc. This does not bring about a large error in the case of long discharges, which are usually used in vortex plasmatrons. Radial profiles of the functions F_1 were calculated from the profiles of the average temperature with the use of data on the temperature dependence of the properties of the air plasma [4-7].

Since the energy supply to a local zone of random superheating of the plasma is dependent on the combined action of Joule dissipation and various heat fluxes, including turbulent heat flux, estimation of the magnitude and sign of the function F_1 does not presuppose compulsory excitation or suppression of thermal turbulence by the conductive heat flux. Therefore, our interest is in estimating the function

$$F_2 = -\frac{4\pi^2}{I^2}\left(r\lambda\frac{dT}{dr}\right)\frac{\left(\int_0^R \sigma r dr\right)^2}{\int_0^r \sigma r dr}, \tag{2}$$

which shows the capability for removing, by conductive energy transfer, the energy of the Joule dissipation released within a circle of radius r. To calculate this function, we also use the radial profiles of the average temperature.

The relative efficiency of radiant energy transfer can be estimated in an approximation of volume radiation. Similarly to (1)

$$F_3 = \frac{4\pi^2 Q_r}{I^2\sigma}\left(\int_0^R \sigma r dr\right)^2. \tag{3}$$

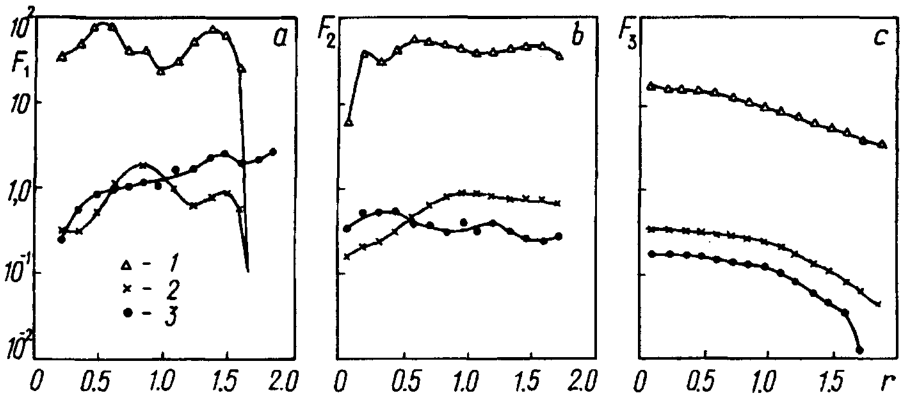


Fig. 2. Radial distributions of the functions F_1 (a), F_2 (b), and F_3 (c) ($d = 8$ mm): 1) $I = 76$ A, $G = 0.2$ g/sec; 2) 80 and 1; 3) 117 and 1.

Estimation of the influence of convective heat flux is most difficult, since it requires a very complicated experiment to measuring the temperature and velocity fields throughout the entire volume of the arc column. These measurements were not performed in this work. Therefore, here no analysis is given of the action of convective fluxes on thermal instability, though convection can be of considerable importance.

The measured profiles of the average temperature are given in Fig. 1. The plots show that an increase in current of from 80 to 117 A did not lead to a pronounced increase in temperature but did produce an increase in the arc diameter. At the same time, the enhancement of arc blowing by increasing the flow rate of the gas leads to a pronounced rise in temperature. Comparison of the temperature profiles for different flow rates enables us to estimate the accuracy of determination of arc column stability by the method of photoscanning.

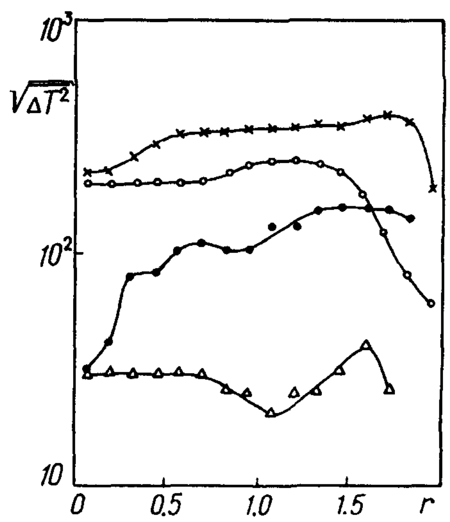
Figure 1 shows that with an increase in the flow rate of the gas of from 1.0 to 4.0 g/sec the expected decrease in the channel diameter did not occur at $I = 80$ A. This indicates the insufficiency of the time resolution of the equipment used. In fact, for an air flow rate of 4 g/sec, the arc column experienced some oscillations, and this caused apparent expansion of its diameter rather contraction. This is also demonstrated by the significantly lower calculated value of the electric-field strength as compared to that measured by experiment.

Figure 2 displays a very strong dependence of the functions $F_1 - F_3$ on the arc conditions. For practically equal currents ($I \simeq 80$ A), a decrease in the flow rate of the gas of from 1.0 to 0.2 g/sec increases them by two orders. This sharp increase in these parameters is due to the substantial decrease in the electric field strength in the arc column with a decreasing flow rate of the gas. Since the Joule dissipation intensity is proportional to the electric-field strength squared, this leads to an abrupt decrease in the energy release in the denominator of functions $F_1 - F_3$. The simultaneous decrease in the numerator due to the decreases in thermal conductivity and emittance with decreasing temperature does not have such a drastic effect.

A comparison of the absolute values of the functions $F_1 - F_3$ for air flow rates of 0.2 and 1.0 g/sec points to qualitatively different effects of the processes of energy transfer on thermal destabilization as the conditions of arcing change. For low flow rates of the gas, the functions $F_1 - F_3$ are much higher than unity over the entire cross-section of the arc column, except for its peripheral region. Under these conditions, thermal turbulization should be strongly suppressed by intense heat removal. As the gas flow rate increases to 1.0 g/sec, the functions F_2 and F_3 turn out to be smaller than unity, and it becomes possible to excite thermal instability.

The current affects the destabilization conditions. For example, Fig. 2 shows that for current $I = 80$ A, F_1 turns out to be smaller than unity on most of the cross-section of the arc column, while for current $I = 117$ A, it is smaller than unity only in the axial zone. This should lead to the attenuation of thermal turbulence with increasing current through conductive energy transfer. Radiant energy transfer has the opposite effect of current variation (Fig. 2c). However, the absolute value of the function F_3 is smaller than the value of F_1. Therefore, we can expect a reduction of the level of thermal destabilization as the current increases from 80 to 117 A.

This conclusion is qualitatively confirmed by measurements of temperature instability in an arc column blown by air. Figure 3 gives the profiles of the root-mean-square values of temperature fluctuations for the same



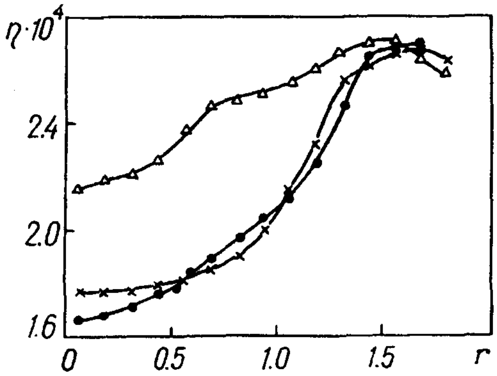


Fig. 3. Radial profiles of the root-mean-square values of temperature pulsations. The notation is in Fig. 1. $\sqrt{\overline{\Delta T^2}}$, K.

Fig. 4. Radial profiles of viscosity in air-blown arc. The notation is in Fig. 2. η, kg/(m·sec).

conditions under which the radial distributions of the average temperature of Fig. 1 were obtained. The figure shows that it is precisely for $G = 0.2$ g/sec that the temperature fluctuations turn out to be small, while an increase in the gas flow rate leads to a sharp enhancement of instability. The conclusion about the reduction in the level of fluctuations with increasing current from 80 to 117 A is justified, too.

Laminarization of a flow in which an electric arc is initiated has been noted [8]. The suppression of hydrodynamic turbulence is explained by the increase in viscosity with temperature. This conclusion is quite justified for air temperature $T < 10.5 \cdot 10^3$ K, which is the case for a "cold" blowing gas and the outer orbit of the arc. It is precisely by the increase in the gas viscosity with current that we can explain the reduction in the level of turbulence for the flow in the external zone and the corresponding decrease in the amplitude of pulsations of the arc column as a whole. As for the interior of the arc column, the viscosity increases with temperature only in its region where $T < 10{,}500$ K. In regions with higher temperatures, the viscosity decreases as the current increases.

In the experiments examined, the viscosity in the central region of the arc decreased with increasing current due to an increase in temperature (Fig. 4). Had there been hydrodynamic turbulence in the arc, its level would have increased with current because of the decrease in viscosity. In actual fact, however, we observe a reduction in the level of instability in the zone of decreased viscosity rather than an increase. The indicated feature, along with the above regularities, provides additional evidence in favor of a thermal character of the excitation of temperature instability within arc discharges.

Figure 3 shows that an increase in the flow rate of the gas of from 1.0 to 4.0 g/sec leads to a decrease in temperature pulsations rather than to their further increase. In this case, it seems impossible to judge more or less correctly the role of conductive energy transfer and radiant energy transfer from the average temperature profiles, because of the "trembling" of the arc column in the gaseous flow. Therefore, the profile of the averaged temperature for $G = 4.0$ g/sec given in Fig. 1 refers to the discharge channel rather than to the arc column. It is possible that the reduction in the level of pulsations is due to the action of convective energy transfer, whose role in the destabilization of individual local regions can be judged only by measuring the temperature and velocity fields throughout the volume of the arc column.

Obviously, the development of thermal instability is also substantially affected by the turbulent heat transfer that occurs in a nonuniform temperature field. Its estimation is most difficult. The turbulent heat flux $q_t \approx \rho h \sqrt{2\Delta h}$ is dependent on the magnitude of the effective enthalpy drop Δh_{eff} within the expanding bubble. This value of Δh_{eff} cannot be determined from the level of temperature fluctuations $\sqrt{\overline{\Delta T^2_{\mathrm{exp}}}}$ measured by experiment, since turbulent energy transfer is governed only by the asymmetry of the expanding superheated zone in a

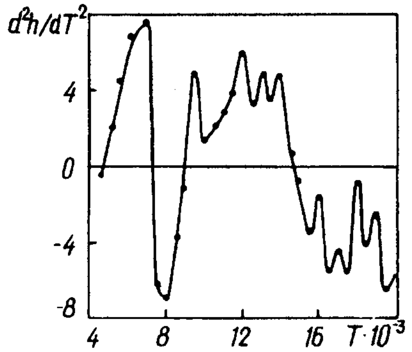


Fig. 5. Second derivative of enthalpy of air plasma with respect to temperature.

nonisothermal plasma. Therefore, for transfer processes that are due to thermal turbulence, we must develop semiempirical approaches, as has been in the case of hydrodynamic turbulence. But the study of thermal turbulence is still in the initial stage, and these methods are still lacking. Nonetheless, the analysis shows that it is possible to make rough estimates of the conditions of occurrence of positive divergence of turbulent heat flux when thermal destabilization begins to develop. Since q_t is mainly governed by the enthalpy $h(T)$ and its effective drop Δh_{eff}, div q_t is positive for $(d^2h/dT^2) > 0$. Figure 5 gives the temperature dependence of the function d^2h/dT^2 for air plasma. The figure shows that the experimental data in question fall into a region favorable to thermal turbulization. However, the outer orbit of the arc column for $T \lesssim 9 \cdot 10^3$ is already unfavorable to the development of thermal turbulence. With greater contraction of the arc column, when the temperature on the arc axis exceeds $\simeq 15 \cdot 10^3$ K, the absence of thermal turbulization in the axial zone can also be expected. Obviously, processes of energy transfer can hinder the turbulization of arc-discharge plasma in a region favorable to thermal destabilization, too; their influence can turn out to be particularly substantial at the edges of this zone, leading to a reduction of its temperature range.

Conclusions. Since the development of thermal instability in an arc-discharge plasma by the thermal-nozzle mechanism occurs in the zone of heat release, this process is affected, by, in addition to Joule dissipation, processes of heat transfer that are dependent on the conditions of arcing. Consideration of the relative role of various mechanisms of energy transfer in an arc discharge blown by air from the experimental data shows that thermal turbulization can develop in greatly contracted arcs with intense energy release when conductive, convective, and radiant heat fluxes are unable to remove the power of Joule dissipation.

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NOTATION

d, discharge chamber diameter; E electric field strength; G, flow rate of air; h, enthalpy; I, electric current; Q_r, volume radiation of plasma; q, specific heat flux; R, arc discharge radius; r, current radius; T, temperature; λ, thermal conductivity; ρ, density; σ, electrical conductivity.

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