Journal of Engineering Physics and Thermophysics, Vol. 70, No. 1, 1997

INFLUENCE OF PLASMA PROPERTIES ON ARC DISCHARGE DESTABILIZATION

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UDC 537.523

The influence of heat transfer processes in arc discharges on the development of thermal instability is considered. A substantial dependence of the process of destabilization on the plasma properties is shown by the example of argon and helium arcs.

Introduction. Electric-arc discharges are currently widely used in various high-temperature technological processes. In particular, electric-arc heating of gases to produce plasma flows to heat materials and to carry out chemical reactions has received wide acceptance. In many cases, the character of the plasma flow is important. In turbulent flows, mixing of the raw material with the plasma and heating of the material are improved. However, in this case, the unwanted process of mixing of the plasma flow with the ambient gas is enhanced, and the jet length and the heating time of the material are reduced.

The character of the generated plasma flow is governed by the processes of interaction between the arc discharge and the heated gas in the discharge chamber of the plasmatron. Turbulization of a gas flow in the presence of an electric arc is substantially different from the development of turbulence in cold flows. When a gas is heated to high temperatures its viscosity increases strongly, thus decreasing the Reynolds number and hindering turbulization. At the same time, the heated flow that blows the arc destabilizes the arc discharge as turbulence develops, inducing its oscillations and bending, which, in turn, contributes to destabilization of the cold flow.

This process of interaction between the arc and the heated gas is also dependent on the electrical parameters of the discharge, since Joule dissipation, which is governed by the current strength, affects the arc temperature and, correspondingly, the thermodynamic and transfer properties of the plasma. But it is on the plasma properties that the characteristics of the arc discharge as the load on an electric circuit are dependent. In the final analysis, there occurs a very complicated process of interaction between the electrical and gas-dynamic parameters, whose regularities are very difficult to establish.

Processes of Arc Discharge Turbulization. The parameters of an arc discharge are substantially dependent on the character of plasma motion in the discharge itself. This problem has received little study. Hydrodynamic turbulence is usually assumed to develop in the arc column, as in the cold flow, when the critical Reynolds number is attained. Correspondingly, in a theoretical consideration, the known methods for determining turbulent friction and thermal conductivity coefficients are used. However, reliable experimental methods for elucidating the character of plasma flow in the arc column remain to be found. There have been only isolated attempts to establish a combined criterion on the basis of gas-dynamic and electrical parameters by which we could calculate the length of the transition zone in the plasmatron's discharge chamber before turbulization of the cold flow starts [1]. The character of gas flow in the arc column that starts to oscillate and to bend remains unclear.

Some authors hold the opposite viewpoint, according to which flow in the arc discharge is always laminar, because of the high viscosity of the plasma. Certain grounds for this viewpoint are provided by the laminarization of the cold flow by the arc discharge [2]. This approach makes it possible to simplify investigation of the complex

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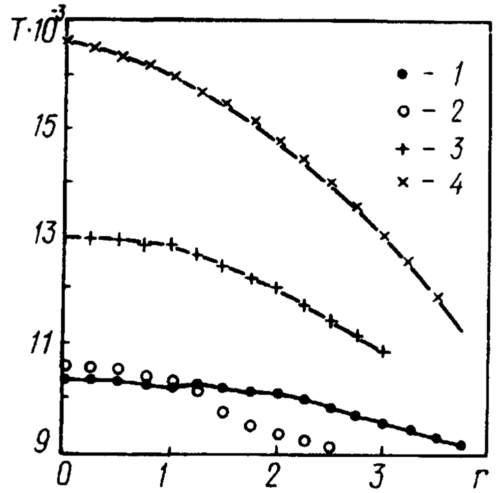
Academic Scientific Complex "A. V. Luikov Institute of Heat and Mass Transfer of the Academy of Sciences of Belarus." Institute of Molecular and Atomic Physics of the Academy of Sciences of Belarus, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 70, No. 1, pp. 93-98, January-February, 1997. Original article submitted October 14, 1994.



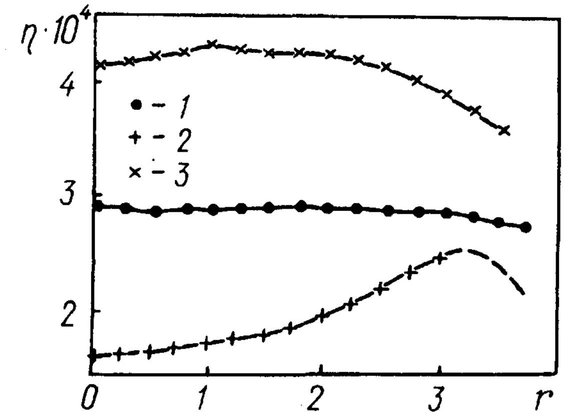


Fig. 1. Radial profiles of average temperature in argon and helium arcs: 1) argon; $d = 10$ mm; $I = 65$ A; $G = 0.1$ g/sec; ArI 696.8 nm [3]; 2) argon; $d = 10$ mm; $I = 65$ A; $G = 7.7$ g/sec; ArI 415.0 nm [3]; 3) argon; $d = 10$ mm; $I = 120$ A; $G = 1.5$ g/sec; ArI 1480.6 nm [5]; 4) helium; $d = 8$ mm; $I = 160$ A; $G = 0.2$ g/sec; HeI 492.3 nm [5]. T, K; r, mm.

Fig. 2. Radial profiles of dynamic viscosity: 1) argon; $d = 10$ mm; $I = 65$ A; $G = 0.1$ g/sec [3]; 2) argon; 10, 120, and 1.5 [5]; 3) helium; 8, 160, and 0.2 [5]. η, kg/m·sec.

problem of the interaction between the arc discharge and the heated flow and to consider only the process of turbulization of the external zone of the heated gas.

Recent attention, however, has been focused on the existence in the arc discharge of thermal turbulence that, unlike hydrodynamic turbulence, develops by converting the heat energy of temperature fluctuations to the kinetic energy of vibrational motion of the plasma rather than due to the kinetic energy of the flow and can occur only inside the column of the discharge arc. In a nonisothermal arc plasma, these oscillations realize energy transfer that is considered by analogy with hydrodynamic turbulence, turbulent heat transfer.

A model of this thermal turbulence is proposed. The essence of the phenomenon is that in random heating of a local region of the plasma, it expands because of the initial increase in pressure. In the process of expansion, the additional energy of Joule dissipation goes to the accelerating flow. In this case, a "thermal nozzle" effect occurs in which, when that consists in the fact that when the heat energy of superheating is converted to kinetic energy, the additional energy supply to subsonic flow is also converted to kinetic energy, increasing the flow velocity in the expanding "bubble." The temperature in the region of stagnation of the accelerated flow can turn out to be higher than the initial temperature. Strong destabilization of the plasma and significant heat transfer can occur due to this positive feedback. Checking of this model showed that it is not at variance with the known experimental data.

Influence of Plasma Properties on Processes of Arc Discharge Turbulization. To assess the influence of the thermodynamic and transfer properties of the plasma on the processes of arc discharge turbulization, we use the experimental data on the instability of argon and helium arcs given in [2-5]. We determine the local equilibrium values of the plasma properties from experimental profiles of the averaged temperature (Fig. 1) and data on the temperature dependence of the properties of argon and helium [6-8].

It is the cold flow blowing the arc that becomes turbulized first, since its viscosity is much lower (the dynamic viscosity of argon and helium at room temperature is $2.11 \cdot 10^{-5}$ and $1.87 \cdot 10^{-5}$ kg/m·sec, respectively). Figure 2 gives the radial distributions of the dynamic viscosity calculated from the profiles of the averaged temperature (Fig. 1) in the arcs in question. The form of these functions is substantially dependent on the temperature on the discharge axis. The viscosity attains its maximum at atmospheric pressure at $T = (10.0-10.5) \cdot 10^3$ K in argon and at $T = 16 \cdot 10^3$ K in helium. Therefore, a decrease in viscosity in the axial region is observed in helium and argon with a higher temperature at the center of the arc.

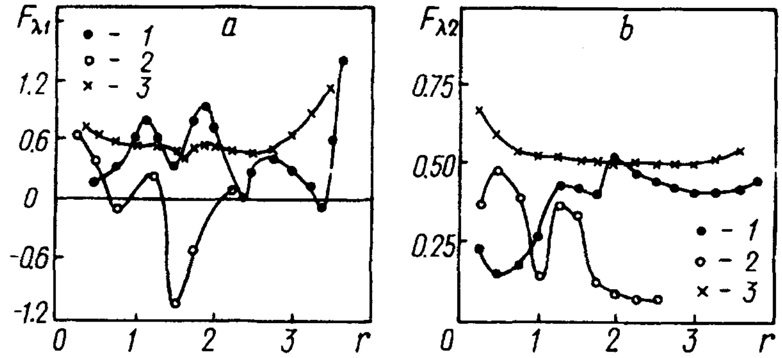


Fig. 3. Radial profiles of functions $F_{\lambda 1}$ and $F_{\lambda 2}$: 1) argon; d = 10 mm; I = 65 A; G = 0.1 g/sec [3]; 2) argon; 10, 65, and 7.7 [3]; 3) helium; 8, 160, and 0.2 [5].

A sharp increase in the viscosity in the arc column keeps the hydrodynamic turbulence from penetrating it from outside. However, turbulence can develop inside the arc column, because of sources of destabilization that are inherent in electric discharges. The development of thermal turbulence turns out to be more probable, since in the subsonic plasma flows characteristic of plasma generators, the thermal energy is much greater than the kinetic energy of the flow.

As follows from the above model of thermal turbulence, for this instability to develop in a local region, the presence of the internal sources of heat release is a necessary condition. Along with Joule dissipation, the release or absorption of energy can be caused by other physical processes, which will manifest itself in a change in the intensity of heat fluxes of various types (convective, conductive, radiant fluxes). Therefore, in addition to the electrical conductivity of the plasma, its other transfer properties play an important role.

Heat removal from a region of the arc column reduces the level of thermal destabilization and can suppress it completely if the heat removal intensity exceeds the supply of energy through Joule dissipation. The process is dependent on the simultaneous action of all modes of energy transfer, and this greatly complicates consideration of the given problem. However, it is not unreasonable to make an effort to assess the influence of individual factors for typical conditions.

Fairly long arcs are used in electric-arc plasmatrons, and when conductive energy transfer is considered the heat removal in the radial direction can be allowed for in a first approximation. In this case, the conductive heat flux is calculated from the radial profile of the average temperature measured experimentally. The supply or removal of energy in individual zones of the arc column will be determined by the divergence of the heat flux. To assess the degree of the influence of conduction on thermal destabilization of the discharge, we compare the divergence of the conductive flux with the Joule dissipation intensity, i.e., determine the magnitude and sign of the function

$$F_{\lambda 1} = -\frac{1}{r}\frac{d}{dr}\left(r\lambda\frac{dT}{dr}\right)/\sigma E^2 . \qquad (1)$$

Under the above assumption, the electric-field strength E will be constant over the cross-section of the arc column. We can determine E experimentally or calculate it from the temperature profile using the dependence $\sigma(T)$

$$E = I/2\pi \int_0^R \sigma r dr . \qquad (2)$$

An uncertainty is introduced by the large error of temperature measurement in the peripheral region of the arc column. However, by extrapolaring the profile $T(r)$ we are able to obtain an E that is in sufficiently good agreement with the experimental measurement data.

The functions $F_{\lambda 1}$ constructed from the average-temperature profiles (Fig. 1) are shown in Fig. 3a. Salient points, that are characteristic of the thermal conductivity of the plasma are evident on the plot. It is also evident

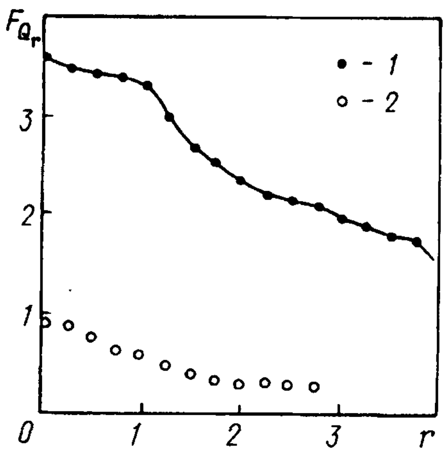


Fig. 4. Radial profiles of function F_{Q_r} in an argon arc (d = 10 mm; I = 65 A):
1) G = 0.1 g/sec; 2) 7.7.

that in the larger portion of the column the thermal conductivity has no substantial effect on the thermal destabilization of the plasma ($F_{\lambda 1} < 1$). However, in individual places $F_{\lambda 1} > 1$, which points to the possibility of suppressing instability, and when $F_{\lambda 1}$ becomes negative, the conductive flux can generate turbulence even without Joule dissipation energy. It is noteworthy that it is precisely in the region $r \approx 1$ mm that the instability peak for the indicated regime was noted in [3]. An increase in heat removal is observed at the periphery of the arc column, which is due to the sharp decrease in temperature in this region.

We should note, however, that individual regions are interconnected by the process of energy transfer rather than isolated. While at a distance from the axis there is intense conductive heat removal, but this is not observed closer to the axis, an additional mechanism of turbulent energy transfer is activated due to the development of instability at a smaller radius. This supply of energy compensates for the conductive heat removal, preventing the suppression of thermal turbulence. Therefore, it is also appropriate to determine the ability of conductive heat transfer at a distance from the axis to remove the entire Joule dissipation energy released inside a given circumference. For this assessment, from the temperature profile we can calculate the function

$$F_{\lambda 2} = -\frac{r\lambda dT/dr}{E^2 \int_0^r \sigma r dr}. \tag{3}$$

Figure 3b gives these functions for argon and helium arcs. The figure demonstrates clearly that conductive heat removal alone is unable to suppress thermal turbulization, since $F_{\lambda 2} < 1$.

Another mechanism that has the ability to markedly affect the process of thermal destabilization is radiant energy transfer. The simplest assessment of this effect is an examination of the relative fraction of body radiation as compared to Joule dissipation. By analogy with (1), it is determined by the expression

$$F_{Q_r} = Q_r/\sigma E^2. \tag{4}$$

Figure 4 demonstrates the influence of radiant energy transfer in an approximation of body radiation on the thermal destabilization of argon arcs. It is evident that the radiation can have a pronounced effect on the process of thermal turbulization. In an argon arc, for G = 0.1 g/sec the radiation intensity exceeds substantially the Joule dissipation over the entire cross-section of the arc column. Thermal turbulization at the center of this arc is possible only for a significant energy supply by convective energy transfer. It should be believed that it is precisely the radiation that is responsible for the suppression of temperature instability in the axial zone of the argon arc for the indicated regime of its arcing. This is confirmed by the results of measuring temperature fluctuations [3]. However, in the peripherical zone of this arc, a growth in instability is noted. The cause could be the absorption of radiation in the external zone of the arc column as well as the supply of energy by convective and conductive fluxes.

An increase in the argon flow rate of from 0.1 to 7.7 g/sec decreased F_{Q_r} sharply. In this regime, $F_{Q_r} < 1$ and the radiation can no longer suppress thermal turbulization, which is shown by experimental measurements of temperature instability in [3]. This exemplifies well the role of the conditions of arcing. Enhancement of the blowing of the arc column increased substantially the electric field strength and Joule dissipation, which led to a sharp decrease in F_{Q_r}.

The radiation of a helium plasma is by 3–4 orders of magnitude weaker than that of an argon plasma. Therefore, in helium arcs radiant energy transfer has no pronounced effect on the processes of thermal turbulization. Here, a certain role can be played by convective heat transfer. It is not improbable that, because of the low intensity of radiation heat transfer, it is precisely in helium arcs that a pronounced predominance of turbulent energy transfer is revealed [4, 5].

An experimental determination of the role of convective energy transfer with the flows of the gas blown through the arc is very difficult, since we must measure the fields of temperatures and velocities for the plasma over the entire volume of the arc. In the long arcs that are used in plasma generators, convective heat transfer occurs predominantly in the axial direction. In the initial section of the arc column, the energy is removed by convective flows, while in the subsequent sections, it is released. Therefore, convective energy transfer can suppress thermal turbulization in the initial section of the column and enhance it in downstream sections. In the zones of variation in arc-column size, enhancement of the radial components of the convective flow can have a pronounced effect on the suppression of thermal turbulence in the axial zone and its enhancement in peripheral regions, when the column expands. The opposite result is obtained when the arc column converges due to blowing.

Conclusions. The study shows a substantial influence of plasma properties on processes of thermal turbulization, since the development of instability is dependent on them. Conductive energy transfer has no pronounced effect on discharge destabilization, while radiation can be play a crucial role. The influence of radiant transfer is particularly substantial in weakly constricted argon arcs with a low electric-field strength. In a helium arc, radiation does not play substantial role, which facilitates the development of thermal turbulence not only at the periphery of the discharge channel but also in its central part. To elucidate the role of convective energy transfer, we must perform comprehensive experiments with measurement of temperature and velocity fields over the entire volume of the arc discharge.

The authors thank the Fundamental Research Fund of the Republic of Belarus for support of the work.

NOTATION

E, electric-field strength; I, electric current; R, radius of arc discharge; r, current radius; T, temperature; Q_r, volumetric emissive power of plasma; λ, thermal conductivity coefficient; σ, electrical conductivity coefficient.

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