FLOW TURBULENCE IN A CYLINDRICAL CHANNEL ENCOMPASSING AN ELECTRIC ARC

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UDC 533.951.7

The effect of an electric arc on the gas flow in a cylindrical channel is investigated. It is shown that the striking of an arc in a laminar flow leads to its turbulence at the boundary of the arc column. Within the arc column, the flow is rendered laminar by the high viscosity of the arc plasma. However, thermal turbulence may develop in the central part of the arc.

Introduction. Arc discharge is used to an ever-increasing extent in various technological plasma processes. In most devices, the arc is insulated from the channel walls by the forced vortical–longitudinal flow of a heated gas. The character of the flow plays an important role both within the arc column and in the external flow. The flow turbulence also affects considerably the arc characteristics and the conditions under which technological processes are carried out in the arc plasma.

The turbulence conditions in the presence of an electric arc in the flow are considerably different from those in a cold flow without an electric arc. In the arc column, the gas temperature and velocity rise sharply, and the gas characteristics change. Thus, the gas viscosity in the arc increases by more than one order of magnitude. For instance, the dynamic air viscosity at room temperature is equal to $184.6 \cdot 10^{-7}$ kg/(m·sec), while, at $T = 10^4$ K, it is equal to $2690 \cdot 10^{-7}$ kg/(m·sec). Moreover, besides the hydrodynamic sources of instability, additional instability sources of a thermal nature develop in the arc [1]. In connection with this, the problem of flow turbulence in a channel with an electric arc is of considerable interest. This pertains to both the effect of the external flow turbulence on the character of gas flow in the arc column and the inverse action of the arc on the flow of a cold gas. However, in spite of the pressing nature of this problem, investigations of turbulence in an electric arc have not yet shed sufficient light on the basic trends in turbulence development, which is due to the difficulties in measuring the fluctuations of the discharge parameters.

We provide below some of the results obtained in investigating thermal instability in laminar and turbulent flows of different gases around an electric arc.

1. *Experimental Investigation of Arc Discharge.* For investigating the instability of the parameters, a dc arc was struck in a cylindrical channel consisting of water-cooled copper disks with a thickness of 5 mm, which were insulated from each other. The channel diameters were equal to 8 and 10 mm, while the channel lengths were equal to 50 and 100 mm. The insulation thickness between the disks (mica, paranite, or organic glass) was equal to 0.3-2.0 mm. A rod cathode (hafnium or tungsten) and a hollow cylindrical or end-face copper anode were used. Different gases were blown through the channel: argon ($G = 0.3$-3.5 g/sec), helium (0.1-0.5), nitrogen (0.5-4.0), and air (1.0-4.0). The current intensity varied from 60 to 250 A.

The mean current value, the voltage, the gas discharge, and the spectral radiation intensity were recorded. Fluctuations of the electric parameters and the radiation flux and acoustic vibrations were also measured. The arc was photographed with a time resolution of 10^{-3} sec and a spatial resolution of 10^{-5} m.

Streak pictures of an arc show that stable arcing without noticeable deviation of the column from the axis is observed at low gas discharge values, which is especially noticeable in the case of argon at $G = 0.3$-0.5 deg/sec at the beginning of the channel ($l/d = 2.5$-3.0). For the assigned current value, the instability gradually increases as the gas discharge and the distance from the cathode increase: There develop transverse column displacements and fluctuations of the radiant flux and the arc diameter. For a constant discharge, the arc diameter increases, while the fluctuations diminish, as the current increases.

Academic Scientific Combine A. V. Lykov institute of Heat and Mass Exchange, Academy of Sciences of Belarus', Minsk. Translated from Inzhenerno-Fizicheski Zhurnal, Vol. 62, No. 4, pp. 601-607, April, 1992. Original article submitted August 2, 1991.

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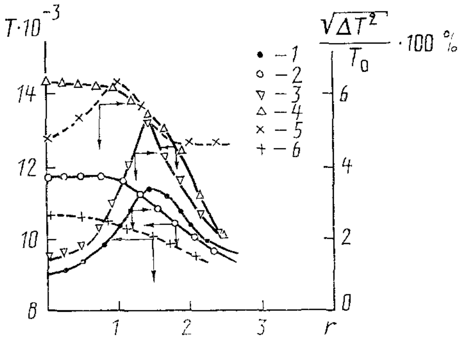

Fig. 1. Distribution of the mean temperature and the relative root-mean-square radial temperature fluctuations in a turbulent-flow channel with a vibrating arc. 1) and 2) Argon (Ar I; 852.1 nm), G = 1.5 g/sec, I = 120 A, d = 0.8 cm, and $Re_{cold} = 10^4$; 3) and 4) air (NI; 742.3 nm), G = 2.0 g/sec, I = 150 A, d = 0.8 cm and $Re_{cold} = 1.7 \cdot 10^4$; 5 and 6) argon (data borrowed from [3], continuum 414.6 nm), G = 7.7 g/sec, I = 65 A, d = 1.0 cm, and $Re_{cold} = 4.3 \cdot 10^4$. The values of T are given in degrees Kelvin, and the values of r are given in millimeters.

Random as well as regular arc vibrations are observed; the vibration frequency depends on the geometric shape of the channel, the type of gas and its discharge, and the current intensity. Thus, in nitrogen and air, intensive random displacements of the arc columns are observed for relatively low currents (I = 70-150 A) and large values of the gas discharges (G = 1-2 g/sec). With an increase in the current to 220 A, at low discharge values (G $\leq$ 1 g/sec), periodic vibrations occur against the background of random vibrations. This process is even more strongly pronounced in helium (I = 140-160 A; G = 0.1-0.3 g/sec), where the percentage of radiation modulation exceeds that in nitrogen or argon by a factor of 3-5. The twisting of the gas flow and the channel length do not affect appreciably the character and frequency of arc column vibrations.

An analysis of the streak pictures indicates that the plasma column vibrates as a whole, without substantial changes in its dimensions.

In recording the radiation from an vibrating arc in the channel, the fluctuations of the radiant flux intensity are determined by perturbations of the parameters of the arc column as well as its displacements. The column vibration frequency reaches $2 \cdot 10^4$ Hz. In this case, in order to separate the vibration of the radiation originating in the arc, it is necessary to measure the radiant flux with a time resolution of not less than 10^{-5} sec. This was ensured by means of time-lapse filming of interferograms at a rate of up to $2.5 \cdot 10^5$ sec^{-1} [2]. However, obtaining instantaneous values of temperature profiles from interferograms is a very time-consuming process. Therefore, we also investigated the possibility of using certain model representations of the radial distribution functions of radiation intensity in the channel and in the arc.

It has been shown that the "gauss–gauss" model can be used for the central part of the arc. According to this model, the radiation intensity distribution, both within the arc column I(x) and in the radial direction in the channel where the arc vibrates J(y), can be approximated by Gaussian functions. The probability of column shift $\psi(x-y)$ also is a Gaussian function.

If there are no arc displacements, the radial intensity distribution of vibrations of the arc parameters in the channel corresponds to the vibration distribution within the arc column. A dip in the variance of radiation fluctuations $\Delta \bar{J}^2(y)$ is usually observed at the chamber axis during column vibrations within the cross section of the channel. The maximum of the radiation variance is located at a certain distance from the channel axis.

The above theoretical conclusion was confirmed by experimental investigations of temperature fluctuations in a turbulent flow. Figure 1 shows the radial profiles of the temperature and its root-mean-square deviation for arcs experiencing vibrations in argon or air flows. The temperature fluctuations are represented in percentages of the maximum mean temperature

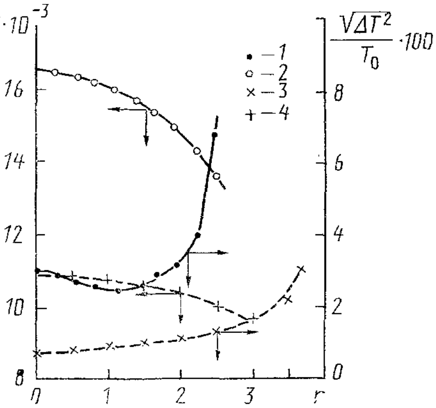

Fig. 2. Distribution of the mean temperature and the relative root-mean-square radial temperature fluctuations in the channel in a laminar flow with a stationary electric arc. 1) and 2) Helium (He I; 492.3 nm), G = 0.2 g/sec, I = 150 A, d = 0.8 cm, and Re_{cold} = 1600; 3) and 4) argon (data borrowed from [3], continuum 414.6 nm), G = 0.1 g/sec, I = 65 A, d = 1.0 cm, and Re_{cold} = 560.

at the channel axis. It is evident that the maximums of the root-mean-square deviations (solid curves) are shifted away from the axis by approximately 1.5 mm in our experiments. The dashed curves have been plotted on the basis of data from [3].

A comparison indicates that the magnitude of temperature fluctuations increases with an increase in the gas discharge and a reduction in the current. The levels of vibration at the channel axis and the outer boundaries of the arc column shifts are approximately equal. For argon, they are lower than the maximum values by about 2%. This difference is larger for air (3-4%).

Due to the arc column vibrations, the mean temperature profiles display a ledge at the center of the discharge channel. The mean temperature starts to drop beyond the boundaries of the vibration region. The example of argon arcs indicates that the mean temperature rises with an increase in the current and a reduction in the discharge channel diameter.

The data given in Fig. 1 pertain to the radial distribution of the mean fluctuating temperature in the discharge channel and the relative amplitude of its fluctuations. However, the similar radial distributions within the arc column are of great interest. Such distributions can be more readily obtained for a nonvibrating arc in a laminar flow. Figure 2 shows the radial distributions of the mean temperature and its fluctuations for a nonvibrating arc in a laminar helium flow (solid curves). The dashed curves are based on data from [3] for an argon plasma.

It is evident from the figure that temperature fluctuations of the order of a few percent of the mean axial temperature occur at the periphery of the arc column in both a helium and an argon plasma. These fluctuations are gradually damped in the axial direction of the arc column. The fluctuations are obviously generated at the boundary between the gas flow and the arc. The high viscosity of the arc plasma prevents these fluctuations from penetrating the arc column. The laminar flow is probably destabilized by the sharp increase in the gas velocity at the boundary of the arc column, which gives rise to considerable shearing stresses in the peripheral region of the arc. In this case, the "peripheral" flow instabilities are hydrodynamic in character.

The temperature fluctuations in an argon arc are damped smoothly, diminishing to a value of less than 1% at the channel axis. In a helium arc, a renewed rise of temperature fluctuations is observed in the central part of the column. Evidently, the action of another source of instability manifests itself in this case. It is assumed that this is a thermal source and that it arises due to the overheat instability of the Joule heat release [4].

These experimental data indicate that the gas flow instabilities at the arc periphery also entail temperature fluctuations. However, these experiments do not provide data indicating whether there is a reverse process at the center of the arc column, i.e., whether the thermal instability leads to hydrodynamic instability. If this process occurs, there must also exist additional

TABLE 1. Relative Root-Mean-Square Deviations of the Generalized VAC of Electric Arcs in Longitudinal–Vortical Flows of Different Gases

Dimensionless number	Deviation				
	argon	helium	air	nitrogen	hydrogen
Π_1	0,298	0,475	0,619	0,274	0,472
Π_2	0,268	0,426	0,334	0,194	0,103
Π_3	0,343	0,402	0,679	0,377	0,574
Π_4	0,289	0,383	0,467	0,308	0,302

turbulent heat and mass exchange. Turbulent energy transfer can be used for checking the effect of thermal instability on thehydrodynamic instability of the flow.

2. *Correlation of the VAC (Volt–Ampere Characteristics) of Arc Discharges.* The energy exchange processes are the main factors influencing the characteristics of an arc discharge. The Joule heat that is released in the arc column can be removed from the arc in various ways: by means of conductive, convective, or radiant heat exchange processes. If the flow is turbulent, the turbulent mechanism of heat exchange may play the main role. Obviously, different energy mechanisms can act simultaneously in an arc, but, depending on the arcing conditions, some processes may be dominant. The character of the dominant heat exchange process can be determined by correlating the discharge characteristics. The probable dominant process is that which is characterized by a dimensionless number providing the minimum root-mean-square deviation of the generalized arc characteristic. The most convenient procedure is to check for the minimum deviation of the generalized VAC of the arc.

The type of the dimensionless number depends on the energy exchange mechanism, which is determined by the arcing conditions [5]. The following heat exchange numbers have been derived for arcs in a longitudinal blow: conduction, $\Pi_1 = \lambda_0 T_0 \sigma_0 d^2/I^2$; convection, $\Pi_2 = \sigma_0 h_0 G d/I^2$; volume radiation, $\Pi_3 = \sigma_0 Q_{\Pi 0} d^4/I^2$. A dimensionless number for turbulent heat exchange has been proposed in [6, 7]. It is given by $\Pi_4 = \rho_0 \sigma_0 h_0^{\,1.5} d^3/I^2$.

Table 1 provides the relative root-mean-square deviations of generalized VAC of the $Ud\sigma_0/I = c\Pi_i^{\alpha_i}$ type for arcs in the longitudinal flow of various media.

The experiments were performed in plasmotrons with self-adjusting arc length. The parameters varied in the following ranges: I = 40-90 A; G_{ar} = 1-12 g/sec; G_{he} = 0.25-4 g/sec; G_{N_2} = 2-6 g/sec; G_{air} = 40-900 g/sec; G_{H_2} = 1-3 g/sec; d = 10-40 mm.

The data given in Table I indicate that convective heat exchange by "through-blow" is dominant for all the gases investigated. This result is characteristic for weakly stabilized arcs in a longitudinal blow, which are ordinarily used in technological devices.

The dimensionless number pertaining to turbulent heat exchange proved to be the dominant one for a helium blow around the arc. This result is in good agreement with data obtained in investigating temperature fluctuations.

3. *Turbulent Heat Exchange Mechanism.* The structure of the turbulent heat exchange number Π_4 indicates that it is similar to the convective heat exchange number Π_2. They both characterize the removal of Joule heat by the gas flow, j^2/σ = div $\rho v h$. The difference consists in the conditions under which the flow velocity develops. In the case of convective heat exchange, the characteristic velocity scale is determined with respect to the assigned discharge of the gas blown through the discharge channel $G = \rho_0 v_0 d^4/4$. In the case of turbulent heat exchange, $v_0 \sim \sqrt{h_0}$. This condition is characteristic of gas acceleration in a nozzle. Consequently, if correlation analysis indicates a substantial role of the Π_4 number, this means that conditions exist in the arc for gas acceleration due to a temperature drop.

Thus, there is reason for a positive answer to the question whether plasma fluxes are generated by the development of temperature instabilities. The nature of these instabilities can be either hydrodynamic or thermal. However, in our case, it was found that, both temperature fluctuations of a thermal nature and the dominant role of turbulent heat exchange are actually observed in a helium arc. Therefore, we draw the conclusion that temperature instabilities of a thermal nature are accompanied by hydrodynamic instabilities.

In correspondence with the above, we can assume that, in local overheat regions, there develop temporary micronozzles, where this overheat is expended on the creation of local microjets. In the case of thermal instability, a nozzle should probably also be of a thermal nature. Therefore, we can write $(1 = M^2)dv/v = dQ/\rho h$ for a thermal nozzle on the basis of the condition for action inversion [8]. The jet heating source Q is a Joule source, and, therefore, $Q = \tau j^2/\sigma$, while the time scale of turbulence τ is related to the spatial scale l by the velocity scale $l = \tau\sqrt{h_0}$.

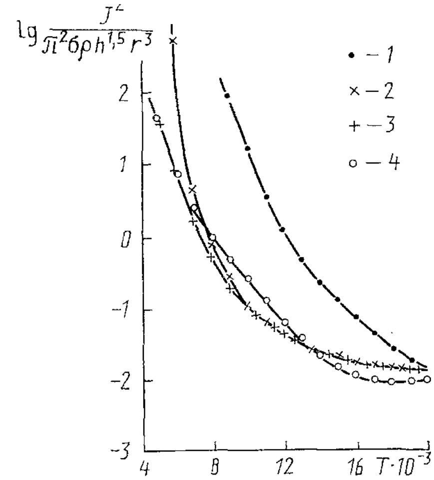

Fig. 3. Dimensionless number $\Pi_5 = I^2/\pi^2\sigma_0\rho_0 h_0{}^{1.5}r^3$ as a function of the temperature; I = 500 A. 1) He (r = 3 mm); 2) N_2 (r = 2.5 mm); 3) air (r = 2.5 mm); 4) Ar (r = 4 mm).

The dimensionless number defining the conditions for the creation of flow in a thermal nozzle is obtained from the above relationships. It is given by $\Pi_5 = I^2/\sigma_0\rho_0 h_0{}^{1.5}r^3$.

This number is actually at a maximum for a helium plasma. This is shown in Fig. 3, which shows the number Π_5 as a function of the plasma temperature for different gases with the correction for the difference between the diameters of the arc channel. Thus, it is in a helium arc that favorable conditions for the development of thermal turbulence obtain.

However, the Π_5 number is a quantity which is the reciprocal of the number $\Pi_4(\Pi_5 = 1/\Pi_4)$. This means that the more effective the turbulent heat exchange, the worse the conditions for the thermal mechanism of microjet formation. Turbulent heat removal suppresses the development of thermal turbulence. However, if thermal instability develops, it is unavoidably accompanied by turbulent heat removal. In comparison with the plasma of other gases, the conditions created in a helium plasma are such that, regardless of the lowest value of Π_4, turbulent heat exchange is the dominant one in an arc exposed to a longitudinal blow.

In comparison with a low-temperature flow, another turbulence source arises at the boundary between the arc column and the gas flow. Due to a sharp rise in the gas velocity in the arc column, large shearing stresses, which lead to flow turbulence, arise at the arc periphery. However, the simultaneous increase in the plasma viscosity causes damping of the periphery turbulence within the column. Therefore, if an arc is struck in a laminar flow, a "three-layer" flow develops due to the peripheral turbulence.

In a turbulent flow, the arc column vibrates, and the maximum of the radial instability distribution is usually shifted away from the channel axis. The instability levels at the channel center and at its periphery are approximately equal. As far as the radial instability distribution in a vibrating arc column is concerned, we did not obtain experimental data for this case because of the complexity of the experiments. However, the VAC correlation does not indicate the presence of a dominant turbulent heat exchange in longitudinal flows around an arc of air, argon, nitrogen, or hydrogen. Therefore, we can assume that damping of peripheral turbulence within the arc column also occurs in a vibrating arc. It would be desirable to confirm this inference by direct measurements of temperature fluctuations.

The most complex flow is the one developing in a channel with a laminar helium flow after an arc is struck. Measurements of temperature fluctuations indicate that we then have a "four-layer" flow. The increase in instability at the arch center is explained by thermal instabilities. For arc discharges, this phenomenon has been observed only in a helium plasma. This could be a consequence of the higher temperature of a helium arc and a larger value of the number Π_5 in comparison with the plasma of other gases.

Conclusions. Our measurements of the thermal instability in electric arcs and the VAC correlation have shown that turbulence arises in a laminar flow in the peripheral region of the arc column when an arc is struck. In a helium arc, a rise of instability is also observed at the center of the arc column. It is assumed that this type of instability is of a thermal nature.

The data which we have obtained are of interest for the plasma technology: plasma chemistry, plasma spraying, fusion, cutting, etc. These results could be used as a basis for new high-temperature procedures, where turbulent heat exchange processes play the main role.

NOTATION

d, channel diameter; G, gas discharge; h, enthalpy; I, arc current; j, current density; l, three-dimensional turbulence scale; Q, heat source; Q_{vo}, volume radiation; r, radius of the arc column; T, temperature; U, arc voltage; v, jet velocity; λ, thermal conductivity; σ, electrical conductivity; ρ, density, τ time scale of turbulence.

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