PROBLEMS IN THE STUDY OF ELECTRICAL ARCS WITH TURBULENT FLOWS

Yu. S. Levitan

UDC 537.523:532.517.4

The unique features of a dc electrical arc burning in a long cylindrical channel with an accompanying flow of plasma-forming gas are considered.

In the development of modern low temperature plasma generators using an electrical arc in a turbulent flow the necessity for reliable methods of calculation and prediction of device characteristics grows ever more important. At present there appears to be a tendency toward significant variation in the geometry of the electrode and flow zones of such generators designed to solve particular problems. On the other hand, in a number of cases for traditional linear type designs the main problem remains increase in output, which is related to increase in energy density, leading to a significant growth in thermal stress of the plasmotron elements and components.

This wide variety of practical problems practically eliminates the possibility of creating any universal calculation method which would consider the entire variety of processes in modern low temperature plasma generators. Hence follows the need for a search for idealized models, which reflect the basic features of processes occurring in real devices. For the devices under consideration these features are as follows: interaction of a nonlinear Joulean heat source (in the present case, the electric arc) with an accompanying turbulent flow of plasma-forming gas, as well as the reciprocal effects of the arc column and the electrode and wall regions. Naturally the presence of some sort of external control actions on the discharge (gas dynamic or electromagnetic) leads to the appearance of additional effects. Some of these have been considered in detail in the literature [1, 2].

The present study will attempt to analyze the features of interation of a dc electric arc with an accompanying flow of plasma-forming gas in the absence of external influences on the discharge. The idealized model of this flow will burn over a long (not less than 50-70 diameters) cylindrical channel, along the axis of which a flow of plasma-forming gas is supplied. In such a model both thermal, and most important, gas dynamic, flow stability is achieved, and moreover, the effect of the discharge column on the electrode zones is reduced to a minimum [3]. The number of studies in which the model described above has been investigated is quite limited (an overview is given in [4]). Nevertheless analysis and generalization of the results obtained therein will permit clarification of interesting principles relating to the transition of laminar into turbulent flow under such conditions.

It should be stressed that in the given case we understand by turbulence a set of fluctuations in gas dynamic and electrical parameters, the amplitude of which significantly exceeds the level of thermal and Langmuir noise.

It develops that data on heat exchange over the stabilization interval can be generalized by three approximate expressions which characterize three different regimes [4]:

laminar flow with unstable arc

$$\left.\begin{array}{r}15<\mathrm{Pe}<20\\ Q>0{,}14\end{array}\right\}\mathrm{Nu}=7.5+2.3Q+1.1Q^2; \qquad (1)$$

laminar regime with stable arc

$$\left.\begin{array}{r}20<\mathrm{Pe}<900\\ Q>0{,}03\end{array}\right\}\mathrm{Nu}=8.0\pm0.1 \qquad (2)$$

Ordzhonikidze Aviation Institute, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 1, pp. 48-53, July, 1989. Original article submitted January 26, 1988.

 0022-0841/89/5701-0766$12.50

fully developed turbulent regime

$$\left.\begin{array}{r}\mathrm{Pe}>900\\ Q>0.9\end{array}\right\}\mathrm{Nu}=7.3+1.2Q-0.015Q^2. \tag{3}$$

Here:

$$Q=\mathrm{Ha}\sqrt{\mathrm{Pe}},\quad \mathrm{Nu}=\frac{IE}{\pi\bar{\lambda}(\bar{T}-T_w)},\quad \mathrm{Pe}=\frac{Gc_p}{\bar{\lambda}d_\text{к}},\quad \mathrm{Ha}=\frac{2\mu_0}{\pi d_\text{к}}\sqrt{\frac{I^3}{\pi\bar{\eta}E}}.$$

The appearance among the defining criteria of the flow crisis in addition to the Peclet number Pe (or the Reynolds number Re) of the additional Hartman criterion (Ha) which characterizes the ratio of magnetic to viscous forces, indicates the special features which distinguish the flow under consideration from classical flow of a liquid or gas in a tube, i.e., the effect of electromagnetic forces on the transition of laminar flow into turbulent.

The results obtained relate to the temperature and pressure range in which effects of radiation reabsorption and nonequilibrium still do not manifest themselves significantly [4].

Fluctuations in the gas dynamic parameters velocity, pressure and temperature generate fluctuations in the following electrical parameters of the electrically conductive medium: the conductivity σ', the electric field intensity $\vec{E}'$, the current density $\vec{j}'$, and the Joulean heat liberation q_V'. Correspondingly the single-point moments subject to definition $\overline{E'^2_i}$, $\overline{\sigma' E_i'}$, $\overline{u_i' E_j'}$ [3] appear in the equations of turbulent motion and energy. Determination of the relationships between these moments and those of the gas dynamic quantities will permit, on the one hand, clarification of the role of electrical fluctuations in the processes of interaction of Joulean heat liberation, and on the other hand, significant refinement of the numerical models of such flows, using the relationships obtained as complements.

In the locally isotropic approximation the nonzero moments containing electrical fluctuations for the case $\vec{\bar{E}}$ = const have the form [5]

$$\begin{gathered}\overline{\sigma'\vec{E}'}=-(1/3)\,\alpha\bar{\sigma}\vec{\bar{E}},\quad \overline{\vec{E}'^2_{\parallel}}=(1/5)\,\alpha\vec{\bar{E}}^2,\\ \overline{\vec{E}'^2_{\perp}}=(2/15)\,\alpha\vec{\bar{E}}^2,\end{gathered} \tag{4}$$

where $\alpha=(\overline{\sigma'^2}/\bar{\sigma}^2)$; $\vec{E}_{\parallel}'$, $\vec{E}_{\perp}'$ are components respectively parallel and perpendicular to $\vec{\bar{E}}$.

The arc current at $\vec{\bar{E}}=(\bar{E},\,0,\,0)$ is equal to

$$\bar{I}=2\pi\int\limits_0^R\bar{\sigma}\bar{E}\left(1+\frac{\overline{\sigma' E_x'}}{\bar{\sigma}\bar{E}}\right)rdr=2\pi\int\limits_0^R\sigma_\text{т}\bar{E}rdr. \tag{5}$$

Here σ_T is the turbulent electrical conductivity, which according to [4] can be expressed in the following form:

$$\sigma_\text{т}=\bar{\sigma}\,[1-(1/3)\,\alpha]. \tag{6}$$

Since under experimental conditions the arc current is usually maintained constant, development of turbulence produces an increase in electrical field intensity to a value (for small α)

$$E_\text{т}=\bar{E}\,[1+(1/3)\,\alpha], \tag{7}$$

which compensates the decrease in electrical conductivity.

We will consider briefly the effect upon turbulence of radiation and deviation from local thermodynamic equilibrium.

In the optically transparent range radiation can lead to a reduction in the level of temperature fluctuations due to reradiation between turbulent "moles." This mechanism appears to a significant degree in intensely radiating gases (argon, xenon), and to a lesser degree in weakly radiating ones (hydrogen, helium). As a result the increase in $\bar{E}$ in the presence of a pulsation temperature field (and hence, conductivity) will be more significant, in accordance with Eq. (7), in weakly radiating gases.

Upon reabsorption of radiation a portion of the radiant energy can be concentrated in local regions of the arc, and thus creating temperature inhomogeneities, can initiate additional temperature fluctuations. The importance of considering the mutual effects of deviation from local thermodynamic equilibrium and turbulence was apparently first noted in [6, 7]. In particular, [6] noted a tendency to intensification of thermal nonequilibrium with increase in flow rate and decrease in arc current. The appearance of such fluctuations is related to the fact that with increasing dependence of electrical conductivity on temperature a superheat instability may appear, which under certain conditions transforms to a superheat temperature turbulence [9]. In turn, temperature fluctuations may initiate fluctuations in the dynamic parameters of velocity and pressure.

Thus, under the conditions considered the temperature turbulence generated by the nonlinear heat source is no longer a "passive impurity" with no effect on flow dynamics, as occurs in turbulent flow of nonisothermal media with constant properties.

We will now consider the evolution of superheat turbulence. For this purpose the energy equation, written for small fluctuations at an arbitrary point A of the flow in the presence of a heat liberation source $q_V(T)$

$$\rho c_p \frac{\partial T'(A)}{\partial t} = \lambda \Delta T'(A) + \frac{dq_V}{dT} T'(A), \tag{8}$$

can be multiplied by T'(B), where B is another arbitrary point; the corresponding equation for T'(B) is then multiplied by T'(A), whereupon we combine and average the equations thus obtained. After taking the Fourier transform of the resultant equation for the correlation function $\overline{T'(A)T'(B)}$ we obtain an equation for the two-point spectral tensor Φ_{AB} [10]

$$\frac{\partial \Phi_{AB}}{\partial t} = \frac{2}{\rho c_p}\left(\frac{dq_V}{dT} - \lambda k^2\right)\Phi_{AB}. \tag{9}$$

Equation (9) describes the evolution of the superheat temperature turbulence in the absence of spatial parameter gradients. After integrating Eq. (9) from t_0 to t for the initial condition $\Phi_{AB}(k, t_0) = \Phi^0_{AB}(k)$ we have

$$\Phi_{AB}(k, t) = \Phi^0_{AB}(k) \exp\left[\frac{2}{\rho c_p}\left(\frac{dq_V}{dT} - \lambda k^2\right)(t - t_0)\right], \tag{10}$$

whence it follows that at $dq_V/dT > 0$ the evolution of temperature turbulence leads to attenuation of pulsations with scales less than $\ell^*_T = 2\pi/k^*$ and increase in those with $\ell_T > \ell^*_T$, where $k^* = [\lambda^{-1}(dq_V/dT)]^{1/2}$.

Analysis of Eq. (10) permits the following conclusions:

1) in systems with nonlinear heat liberation the appearance of "long-lived" coarse scale $(l_T \gg l^*_T)$ and high temperature formations against a background of fine scale $(\ell_T < \ell^*_T)$ attenuating temperature turbulence is possible;

2) cascade energy transport in such systems is accomplished from large wave numbers to small ones, i.e., opposite to the transport direction characteristic of a homogeneous and isotropic hydrodynamic turbulence.

In connection with this the following question becomes of principal importance: how do the features of nonlinear heat source interaction with the turbulent flow noted above affect the level of pulsation kinetic energy in the absence of spatial parameter gradients?

Theoretical computations using the simplest possible gradient models have shown the laminarizing effect of Joulean heat liberation, especially in the axial region of the arc channel where the temperature is maximal. This is a consequence of the fact that the turbulent transport coefficients calculated by such models are proportional to gas density [3]. Experimental proof of this laminarization effect is impeded by the low sensitivity of the measurable integral arc plasma characteristics to gas dynamic fluctuations, as well as the laminarizing role of radiation noted above, especially in the high temperature axial regions [3, 11].

When energy is transported from high wave numbers to low ones, as occurs in development of superheat instability, temperature turbulence, as was noted above, will initiate additional velocity fluctuations with an analogous energy cascade process. Since this process will be opposed to the existing background gas dynamic turbulence, their interaction should eventually lead to increase in the "effective" viscosity of the medium, i.e., essentially, to a reduction in the level of kinetic energy pulsation. Such "competition" of the two oppositely directed cascade processes causes the appearance of a most probable mean statistical "vortex" or "mole" size, which formations serve as the basis for a coherent structure [10]. Such structures can obviously be observed in those regions of the flow where transit times are greater than characteristic structure formation times, which in turn are less than diffusion "resorption" times.

In contrast to the model described above, another situation can be realized: a free hot electric arc in a long channel having practically no influence on the characteristics of the turbulent flow within the channel. In this case one can now speak of the arc as a "passive impurity" [1]. The arc column then behaves like a "Brownian" particle, supported from below by impacts from turbulent moles. Such arc behavior is possible if first, the intrinsic electromagnetic forces developed therein are weak in comparison to the flow inertial forces, and second, if Joulean heating of the flow by the arc is small in comparison to the flow thermal content. These conditions can be expressed in the form of the inequalities

$$\bar{j}B_0 \ll \bar{\rho}\frac{\overline{u^2}}{L}, \quad B_0 = \frac{\mu_0 \bar{I}}{\pi d}; \tag{11}$$

$$\bar{I}\bar{E} \ll G\bar{c}_p\frac{\bar{T}}{L}, \tag{12}$$

where B_0 is the maximum value of the magnetic field induction.

After simple transformations we can reduce these expressions to the form

$$\begin{gathered} \bar{I} \ll 2G(\mu_0\bar{\rho}Ld_к\delta^3)^{-1/2}, \\ \bar{I} \ll G\bar{c}_p\bar{T}(\bar{E}L)^{-1}, \end{gathered} \tag{13}$$

where $\delta = (d_c/d) > 1$.

Estimates with Eq. (13) for atmospheric-pressure argon at $\bar{T} = 5000$ K, $G = 1.5 \cdot 10^{-2}$ kg/sec, $\bar{E} = 10^3$ V/m, $d_c = 3 \cdot 10^{-2}$ m, L = 0.6 m, and $\delta = 5$ show that for these for those parameters the arc will behave like a "passive impurity" if $\bar{I} \leqslant 10$ A. As is evident from Eq. (13), the limiting current will increase with increase in mass flow rate and mean mass temperature of the flow. It is just this case in which it is completely correct to use the arc as a flow turbulence sensor [12].

In conclusion, it is important to stress that in developing and refining models for an arc in a turbulent flow it is necessary to consider both the unique features related to interaction of the Joulean heat source with gas dynamic turbulence, and possible states in which the arc appears as a "passive impurity."

NOTATION

G, gas flow rate, kg/sec; u, gas velocity, m/sec; t, time, sec; T, gas temperature, K; ρ, gas density, kg/m^3; I, arc current, A; E, electric field intensity, V/m; d, arc column diameter, m; d_c, channel diameter, m; L, channel length, m; R, r, channel radius and current radius, m; j, current density, A/m^2; q_V, volume heat source intensity, W/m^3; B, magnetic field induction, T; c_p, specific heat of gas, J/(kg·deg); λ, gas thermal conductivity coefficient, W/(m·deg); η, $\bar{\sigma}$, plasma dynamic viscosity and electrical conductivity coefficients; Φ_{AB}, two-point spectral temperature pulsation tensor, deg^2·m^3; k, wave number, m^{-1}; $\mu_0 = 4\pi \cdot 10^{-7}$ Wb/(A·m), magnetic constant; $\alpha = \overline{\sigma'^2}/\bar{\sigma}^2$; $\delta = d_c/d$; prime and overbar denote pulsation and averaged quantities.

LITERATURE CITED

1. M. F. Zhukov, A. S. An'shakov, I. M. Zasypkin, et al., Electrical Arc Generators with Interelectrode Inserts [in Russian], Novosibirsk (1981), pp. 99-107, 189-193.
2. M. F. Zhukov, B. N. Devyatov, O. Ya. Novikov, et al., Thermal Plasma Theory. 4.2. Transient Processes and Radiant Heat Exchange in a Thermal Plasma [in Russian], Novosibirsk (1987), pp. 62-74.

3. Yu. S. Levitan, Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 10, 2, 117-137 (1984).
4. Yu. S. Levitan, Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 16, 3, 74-80 (1986).
5. V. I. Artemov, A. B. Vatazhin, Yu. S. Levitan, and O. A. Sinkevich, Teplofiz. Vys. Temp., 22, No. 4, 720-727 (1984).
6. A. I. Ivlyutin, Materials of the VII All-Union Conference on Low Temperature Plasma Generators, Vol. 2 [in Russian], Alma-Ata (1977), pp. 27-30.
7. A. I. Ivlyutin, Materials of the X All-Union Conference on Low Temperature Plasma Generators, Part 1 [in Russian], Kaunas (1986), pp. 8-9.
8. L. N. Panasenko, Materials of the X All-Union Conference on Low Temperature Plasma Generators, Part 1 [in Russian], Kaunas (1986), pp. 10-11.
9. V. I. Artemov, Yu. S. Levitan, and O. A. Sinkevich, Pis'ma Zh. Tekh. Fiz., 10, No. 7, 413-416 (1984).
10. Yu. S. Levitan, Zh. Tekh. Fiz., 55, No. 2, 434-436 (1985).
11. N. F. Aleshin, A. F. Bublievskii, and O. P. Yas'ko, Materials of the VII All-Union Conference on Low Temperature Plasma Generators, Part 1 [in Russian], Novosibirsk (1980), pp. 36-39.
12. Yu. P. Grigaitis, Materials of the X All-Union Conference on Low Temperature Plasma Generators, Part 1 [in Russian], Kaunas (1986), pp. 35-36.

EFFECT OF THE STARTING TEMPERATURE OF A PLASMA JET ON THE CHANGE IN ITS AXIAL PARAMETERS

Ya. Z. Tikhonovich, V. S. Mirgorodskii, and I. S. Burov

UDC 621.793:533.9

The effect of the starting temperature of a submerged argon plasma jet on its axial parameters is studied, and their dependences on dimensionless gas density from 11 to 81 are obtained.

Mathematical modeling and numerical computation are an effective method for studying processes occurring with the plasma deposition of protective coatings. In developing engineering methods for calculating the motion and heating of the particles of powder [1] it is necessary to employ dependences that describe the change in the velocity and excess heat content of the gas mixture on the axis of the jet. It is well known that on the main section of the jet these parameters drop rapidly owing to intense mixing of the high-temperature gas with the surrounding medium. Increasing the starting temperature of the jet

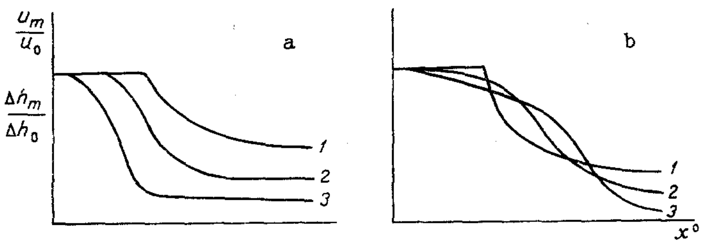

Fig. 1. The dimensionless velocity and excess heat content of gas along the axis of an argon plasma jet as a function of its starting temperature: 1) T_{01}; 2) T_{02}; 3) T_{03}; $T_{01} < T_{02} < T_{03}$; a) calculation using (1)-(2); b) from [6, 7].

Belorussian Republic Scientific-Production Union of Powder Metallurgy, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 1, pp. 54-56, July, 1989. Original article submitted December 24, 1987.

 0022-0841/89/5701-0770$12.50