AN ELECTRICAL ARC IN A TURBULENT GAS FLOW

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The self-similar solution of the equations describing an axisymmetric electrical arc in a turbulent gas flow is presented.

Electrical arc stabilization in a plasmotron is often accompliehed by supplying gas to the discharge chamber with a tangential velocity [1]. Some studies have been dedicated to experimental investigation of an arc under such conditions [2], but they are mainly of a qualitative character. The theoretical approach is beset with great difficulties, so that available studies deal with an idealized formulation [3]. Plasma flow with intense gasdynamic or abrupt geometric compression (for example, by a diaphragm, etc.) has not been studied thoroughly either experimentally or theoretically. In such cases solution of the problem requires use of a complete set of equations: Navier–Stokes, Maxwell's, and energy equations.

In the present study we will consider arc discharge zones with the following assumptions: the plasma is in equilibrium and the flow is steady state; within the arc zone ρ = const, μ = const, λ_t/c_p = const; viscous dissociation and radiant losses will be neglected, as will kinetic energy of the flow; electrical conductivity will depend only on temperature, i.e., $\sigma = \sigma(h)$.

We introduce the dimensionless quantities $\bar{z} = z/R_0$, $\bar{r} = r/R_0$, $\bar{p} = p/\rho u_0^2$, $\bar{h} = (h - h_0)/h_0$, $\bar{u} = u/u_0$, $\bar{v} = v/u_0$, $\bar{\Gamma} = \Gamma/\Gamma_0$, $\bar{\sigma} = \sigma/\sigma_0$, $\bar{\varkappa} = \varkappa/\varkappa_0$, $\bar{E}_z = E_z/E_0$, $\bar{E}_r = E_r/E_0$, $\bar{B} = B_\varphi/B_0$. Here the subscript 0 denotes some constant base parameters, in particular h_0 is the enthalpy at the boundary of the arc, $\varkappa_0 = I/2\pi$.

In this case the system of dimensionless equations describing the parameters of an axisymmetric arc discharge can be written in the form [4]

$$\frac{\partial(\bar{u}\bar{r})}{\partial\bar{z}} + \frac{\partial(\bar{v}\bar{r})}{\partial\bar{r}} = 0, \tag{1}$$

$$\bar{u}\frac{\partial\bar{u}}{\partial\bar{z}} + \bar{v}\frac{\partial\bar{u}}{\partial\bar{r}} = -\frac{\partial\bar{p}}{\partial\bar{z}} + \frac{1}{\mathrm{Re}}\left[\frac{\partial^2\bar{u}}{\partial\bar{z}^2} + \frac{1}{\bar{r}}\frac{\partial}{\partial\bar{r}}\left(\bar{r}\frac{\partial\bar{u}}{\partial\bar{r}}\right)\right] + \frac{\sigma_0 E_0 B_0 R_0}{\rho u_0^2}\bar{j}_r\bar{B}, \tag{2}$$

$$\bar{u}\frac{\partial\bar{v}}{\partial\bar{z}} + \bar{v}\frac{\partial\bar{v}}{\partial\bar{r}} - \frac{\bar{\Gamma}^2}{\bar{r}^3}\frac{1}{\mathrm{Ro}^2} = -\frac{\partial\bar{p}}{\partial\bar{r}} + \frac{1}{\mathrm{Re}}\left[\frac{\partial^2\bar{v}}{\partial\bar{z}^2} + \frac{\partial}{\partial\bar{r}}\left(\frac{1}{\bar{r}}\frac{\partial}{\partial\bar{r}}(\bar{r}\bar{v})\right)\right] - \frac{\sigma_0 E_0 B_0 R_0}{\rho u_0^2}\bar{j}_z\bar{B}, \tag{3}$$

$$\bar{u}\frac{\partial\bar{\Gamma}}{\partial\bar{z}} + \bar{v}\frac{\partial\bar{\Gamma}}{\partial\bar{r}} = \frac{1}{\mathrm{Re}}\left[\frac{\partial^2\bar{\Gamma}}{\partial\bar{z}^2} + \bar{r}\frac{\partial}{\partial\bar{r}}\left(\frac{1}{\bar{r}}\frac{\partial\bar{\Gamma}}{\partial\bar{r}}\right)\right], \tag{4}$$

$$\bar{u}\frac{\partial\bar{h}}{\partial\bar{z}} + \bar{v}\frac{\partial\bar{h}}{\partial\bar{r}} = \frac{1}{\mathrm{Pe}}\left[\frac{\partial^2\bar{h}}{\partial\bar{z}^2} + \frac{1}{\bar{r}}\frac{\partial}{\partial\bar{r}}\left(\bar{r}\frac{\partial\bar{h}}{\partial\bar{r}}\right)\right] + \frac{\sigma_0 E_0^2 R_0 c_p}{\lambda_t h_0}\frac{1}{\mathrm{Pe}}(\bar{j}_z\bar{E}_z + \bar{j}_r\bar{E}_r), \tag{5}$$

$$\frac{\partial}{\partial\bar{z}}\left(\frac{1}{\bar{\sigma}\bar{r}}\frac{\partial\bar{\varkappa}}{\partial\bar{z}}\right) + \frac{\partial}{\partial\bar{r}}\left(\frac{1}{\bar{\sigma}\bar{r}}\frac{\partial\bar{\varkappa}}{\partial\bar{r}}\right) = 0, \tag{6}$$

$$\bar{j}_z = \frac{\varkappa_0}{\sigma_0 E_0 R_0^2}\frac{1}{\bar{r}}\frac{\partial\bar{\varkappa}}{\partial\bar{r}}, \quad \bar{j}_r = -\frac{\varkappa_0}{\sigma_0 E_0 R_0^2}\frac{1}{\bar{r}}\frac{\partial\bar{\varkappa}}{\partial\bar{z}}, \tag{7}$$

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 2, pp. 272-278, February, 1985. Original article submitted November 21, 1983.

$$B = \frac{\mu_e \varkappa_0}{B_0 R_0} \frac{\bar{\varkappa}}{\bar{r}} \tag{8}$$

with boundary conditions $\bar{r}=0$: $\frac{\partial \bar{u}}{\partial \bar{r}} = \frac{\partial \bar{h}}{\partial \bar{r}} = \bar{\Gamma} = \bar{\varkappa} = \bar{v} = 0$, $\bar{r} = \bar{R}(\bar{z})$: $\bar{u} = \bar{u}_R(\bar{z})$, $\bar{v} = \bar{v}_R(\bar{z})$, $\bar{\Gamma} = \bar{\Gamma}_R(\bar{z})$, $\bar{p} = \bar{p}_R(\bar{z})$, $\bar{\varkappa} = 1$, $\bar{h} = 0$. Here $\bar{R}(\bar{z})$ is the boundary of the electric arc ($\sigma = 0$).

The boundary conditions on the "faces" of the arc ($z = 0$ and $\bar{z} = \bar{z}_0$) will not be considered, since we are seeking a self-similar solution of system (1)-(8).

It can easily be proved that in the system of dimensionless equations obtained, aside from the known similarity criteria — the Prandtl, Reynolds, and Rossby numbers — there are four more dimensionless parameters, relating four arbitrary base values. We define these from the conditions

$$\frac{I}{2\pi\sigma_0 E_0 R_0^2} = 1, \quad \frac{\sigma_0 E_0^2 R_0^2 c_p}{\lambda_t h_0} = 1, \quad \frac{\rho u_0^2}{\sigma_0 E_0 R_0 B_0} = 1, \quad \frac{B_0}{\mu_e R_0 \sigma_0 E_0} = 1,$$

whence we obtain the following base values of the corresponding quantities:

$$R_0 = \frac{I}{2\pi}\sqrt{\frac{c_p}{\lambda_t \sigma_0 h_0}}, \quad E_0 = \frac{2\pi}{I}\frac{\lambda_t h_0}{c_p}, \quad B_0 = \mu\sqrt{\frac{c_p}{\lambda_t \sigma_0 h_0}},$$

$$u_0 = \sqrt{\mu_e \frac{\lambda_t \sigma_0 h_0}{\rho c_p}}.$$

The Reynolds and Rossby numbers take on the form

$$\mathrm{Re} = \frac{1}{2\pi}\frac{1}{\mu}\sqrt{\mu_e \rho}, \quad \mathrm{Ro} = \frac{I}{2\pi}\frac{1}{\Gamma_0}\sqrt{\frac{\mu_e}{\rho}}.$$

Estimates show that at $I \sim 10^2$ A, $h \sim 10^7$ J/kg, $\sigma \sim 10^3$ 1/Ω·m, $\rho \sim 10^{-2}$ kg/m³, we have $u_0 = 10$ m/sec, $R_0 \sim 10^{-2}$ m, $E_0 \sim 10^3$ V/m, Re ~ 10.

We will approximate electrical conductivity as a function of enthalpy in the form

$$\sigma = \sigma_0 \bar{h}^n. \tag{9}$$

Performing the replacement of variables $\bar{\eta} = \bar{r}/\bar{R}(\bar{z})$, $\bar{z} = z$ in system (1)-(8), we find that if Eq. (9) is valid, then at $\bar{R}(\bar{z}) = \lambda\bar{z} + \mathrm{const}$ the following self-similar solution of Eqs. (1)-(8) exists:

$$\bar{u} = \frac{\tilde{u}(\eta)}{\bar{R}}, \quad \bar{v} = \frac{\tilde{v}(\eta)}{\bar{R}}, \quad \bar{\Gamma} = \tilde{\Gamma}(\eta), \quad \bar{p} = \frac{\tilde{p}(\eta)}{\bar{R}^2},$$
$$\bar{h} = \frac{\tilde{h}(\eta)}{\bar{R}^{\frac{2}{1+n}}}, \quad \bar{\varkappa} = \tilde{\varkappa}(\eta), \quad \bar{E}_z = \frac{1}{\eta\tilde{h}^n(\eta)}\frac{d\tilde{\varkappa}}{d\eta}\frac{1}{\bar{R}^{\frac{2}{1+n}}}, \tag{10}$$
$$\bar{E}_r = \frac{\lambda}{\tilde{h}^n(\eta)}\frac{d\tilde{\varkappa}}{d\eta}\frac{1}{\bar{R}^{\frac{2}{1+n}}}, \quad \bar{B} = \frac{\tilde{\varkappa}(\eta)}{\eta}\frac{1}{\bar{R}}.$$

Considering Eq. (10), after simple transformations Eqs. (1)-(8) can be reduced to the form

$$\tilde{v} = \lambda\left(\tilde{u}\eta - \frac{1}{\eta}\int_0^\eta \tilde{u}\,\eta\,d\eta\right), \tag{11}$$

$$(\tilde{v}-\lambda\eta\tilde{u})\,\tilde{u}'-\lambda u^2\eta = 2\lambda\tilde{p}+\lambda^2\eta^2\tilde{p}'+\frac{2}{\mathrm{Re}}\lambda^2\eta\tilde{u}+(1+4\lambda^2\eta^2)\frac{1}{\mathrm{Re}}\tilde{u}'+\frac{1}{\mathrm{Re}}(\eta+\lambda^2\eta^3)\,\tilde{u}''+\lambda\tilde{\varkappa}\tilde{\varkappa}', \tag{12}$$

$$(\tilde{v}-\lambda\eta\tilde{u})\,\tilde{v}'-\lambda\tilde{u}\,\tilde{v}\eta = -\eta\tilde{p}'-\frac{1}{\mathrm{Ro}^2}\frac{\tilde{\Gamma}^2}{\eta^2}+\frac{1}{\mathrm{Re}}\left(2\lambda^2\eta-\frac{1}{\eta}\right)\tilde{v}+(1+4\lambda^2\eta^2)\frac{1}{\mathrm{Re}}\tilde{v}'+\frac{1}{\mathrm{Re}}(\eta+\lambda^2\eta^3)\,\tilde{v}''-\frac{\tilde{\varkappa}\tilde{\varkappa}'}{\eta}, \tag{13}$$

$$(\tilde{v}-\lambda\eta\tilde{u})\,\tilde{\Gamma}' = \frac{1}{\mathrm{Re}}(1+\lambda\eta^2)\,\tilde{\Gamma}''+\left(2\lambda^2\eta-\frac{1}{\eta}\right)\frac{1}{\mathrm{Re}}\tilde{\Gamma}', \tag{14}$$

$$(\tilde{v}-\lambda\eta\tilde{u})\,\tilde{h}'-\frac{2\lambda}{1+n}\eta\tilde{u}\tilde{h} = \frac{1}{\mathrm{Pe}}(\eta+\lambda^2\eta^3)\,\tilde{h}''+\frac{2\lambda^2}{\mathrm{Pe}}\eta\frac{3+n}{(1+n)^2}\tilde{h}+$$
$$+\frac{1}{\mathrm{Pe}}\left[\frac{2\lambda^2(3+n)}{1+n}\eta^2+1\right]\tilde{h}'+\frac{1}{\mathrm{Pe}}(\beta_z^2+\lambda^2\beta_r^2)\,\eta\tilde{h}^n, \tag{15}$$

$$\left(\frac{2}{1+n}\lambda^2\eta^2-1\right)\frac{\tilde{\varkappa}'}{\tilde{h}^n}+(\eta+\lambda^2\eta^3)\left(\frac{\tilde{\varkappa}'}{\tilde{h}^n}\right)'=0. \tag{16}$$

The boundary conditions for system (11)-(16) are

$$\begin{gathered}\eta=0:\ \tilde{\Gamma}=\tilde{\varkappa}=\tilde{u}'=\tilde{h}'=0;\\ \eta=1: \tilde{\Gamma}=1,\ \tilde{\varkappa}=1,\ \tilde{u}=\tilde{u}_*,\ \tilde{v}=\tilde{v}_*,\ \tilde{p}=\tilde{p}_*,\ \tilde{h}=0,\end{gathered} \tag{17}$$

where $\beta_z=\frac{1}{\eta\tilde{h}^n}\tilde{\varkappa}';\ \beta_r=\frac{\lambda}{\tilde{h}^n}\tilde{\varkappa}'\left(\tilde{\varkappa}'=\frac{d\tilde{\varkappa}}{d\eta};\ \tilde{\varkappa}''=\frac{d^2\tilde{\varkappa}}{d\eta^2}\right)$. We do not write the integral condition for total flow conservation, since it is satisfied automatically upon introduction of the electric current function. Considering energy loss to radiation in the form

$$q_r=q_0\tilde{h}^{2+n},\qquad \bar{q}_r=\tilde{h}^{2+n}(\eta)\frac{1}{\bar{R}^{\frac{2(2+n)}{1+n}}}\left(\bar{q}_r=\frac{q_r}{q_0}\right),$$

we obtain one more dimensionless complex in Eq. (5). If in boundary conditions (17) we take $\tilde{v}(1)=\tilde{v}_*$, then from Eq. (11) we can find the plasma flow rate through the arc column section

$$Q=\int_0^1\tilde{u}\eta d\eta=\tilde{u}_*-\frac{\tilde{v}_*}{\lambda}. \tag{18}$$

The pressure $\tilde{p}$ is determined from Eq. (13) by integration over η. The value $\tilde{p}(1)=\tilde{p}_*$ at $\eta=1$ is unknown, and therefore $\tilde{p}_*$ must be found from condition (18).

In the calculations performed below, boundary conditions are specified for v_* or Q (which in principle is the same thing), while the value of p(1) is determined by the condition of satisfaction of condition (18).

Integrating Eqs. (14) and (16), we obtain

$$\tilde{\Gamma}(\eta)=C_W\int_0^\eta\exp\left(\int_1^\eta\frac{2\lambda^2\eta^2-1+\lambda\,\mathrm{Re}\int_0^\eta\tilde{u}\eta d\eta}{\eta+\lambda^2\eta^3}d\eta\right)d\eta, \tag{19}$$

$$\tilde{\varkappa}(\eta)=C_\varkappa\int_0^\eta\frac{\tilde{h}^n\eta}{(1+\lambda^2\eta^2)^{\frac{3+n}{2(1+n)}}}d\eta. \tag{20}$$

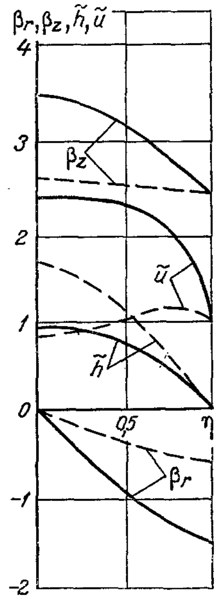

Fig. 1

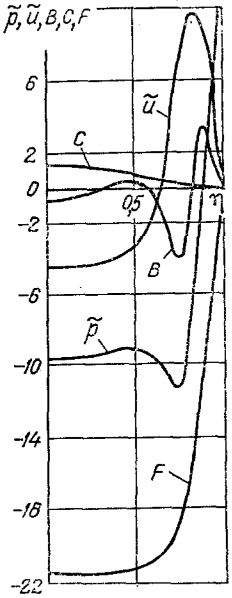

Fig. 2

Fig. 1. Change in electric field intensity components (β_r, β_z), axial velocity component ($\tilde{u}$), and enthalpy ($\tilde{h}$) over arc section. Solid lines, Q = 0.1, λ = −0.6; dashed lines, Q = 0.5, λ = −0.25.

Fig. 2. Change in pressure ($\tilde{p}$), axial velocity component ($\tilde{u}$), and integral quantities B, C, and F over arc section. Re = 10, Ro = 0.1, Q = 1, $\bar{u}$ = 1.

The constants C_W and $C_\varkappa$ are found from the condition $\tilde{\Gamma}(1)=1,\ \tilde{\varkappa}(1)=1$.

In solving system (11)-(16) the parameter λ must be found from an additional condition, which proves to be the integral law of conservation of energy. If we integrate Eq. (5) in the new variables $\bar{z}$, η over η from 0 to 1, we obtain a second-degree ordinary differential equation in λ. With consideration of Eq. (10) this equation degenerates into a second-degree algebraic equation in λ:

$$\left[\tilde{h}'(1)-\frac{2n(1-n)}{(1+n)^2}\int_0^1\tilde{h}\eta d\eta+\int_0^1\frac{\tilde{\varkappa}'^2}{\tilde{h}^n}\eta^3 d\eta\right]\lambda^2+ \tag{21}$$

$$+\operatorname{Pe}\frac{1-n}{1+n}\int_0^1\tilde{u}\tilde{h}\eta\lambda+\tilde{h}'(1)+\int_0^1\frac{\tilde{\varkappa}'^2}{\tilde{h}^n}\eta d\eta=0.$$

It follows from analysis of the self-similar solutions (19), (20) that:

1. The dependence of electric field intensity on $\bar{R}(\bar{z})$ has the form $E\sim\bar{R}^{-\frac{2}{1+n}}$. For real gases the exponent n varies within the range $0<n\leqslant 1$. For air n ∿ 0.5 and E ∿ $\bar{R}^{-1.33}$.

2. The axial component of the electric field intensity β_z is a monotonically decreasing function of η:

$$\beta_z=\frac{C_\varkappa}{(1+\lambda^2\eta^2)^{\frac{3+n}{2(1+n)}}},\quad \beta_z'(\eta)\leqslant 0.$$

This is also true of the modulus of the electric field vector

$$|\beta| = \sqrt{\beta_z^2 + \beta_r^2} = \frac{C_\varkappa}{(1 + \lambda^2\eta^2)^{\frac{1}{1+n}}}.$$

3. The radial component of the intensity β_r may be a nonmonotonic function of η:

$$\beta_r = \frac{\lambda C_\varkappa \eta}{(1 + \lambda^2\eta^2)^{\frac{3+n}{2(1+n)}}}.$$

This is true because the function

$$\beta_r' = \frac{\lambda C_\varkappa \left(1 - \lambda^2\eta^2 \dfrac{2}{1+n}\right)}{(1 + \lambda^2\eta^2)^{\frac{5+3n}{2(1+n)}}}$$

may change sign at the point $\eta_* = \frac{1}{|\lambda|}\sqrt{\frac{1+n}{2}}$; at $|\lambda| = 1$ and $n = 0.5$ we obtain $\eta_* = 0.8$.

4. If $|\lambda| \ll 1$, then from system (11)-(16) we can obtain an equation of the boundary layer type; in this case $\beta z \sim$ const, $\beta_r = 0$.

The solution of system (11)-(16) depends on six parameters. Study of their effect on the solution is a complex problem, since change of one or the other parameter induces change in the entire solution. Calculations have shown that the solution of Eqs. (11)-(16), (21) for specified $\tilde{u}_*$, Q, Re, Ro, Pr, and n exists only for one value of λ. In determining the pressure in Eq. (13) only inertial and magnetic forces were considered, i.e.,

$$\tilde{p}(\eta) = \frac{1}{\mathrm{Ro}^2}\frac{\tilde{\Gamma}^2}{\eta^3} + \lambda\tilde{u}\tilde{v} - (\tilde{v} - \lambda\eta\tilde{u})\tilde{v}' - \frac{\tilde{\varkappa}\tilde{\varkappa}'}{\eta^2}.$$

Results of calculating these equations are presented in Figs. 1-4 for Pr = 0.5 and n = 0.5 and several values of Re, Ro, Q, and $\tilde{u}_*$. Change in the electrical field intensity (β_z, β_r), axial velocity ($\tilde{u}$), and enthalpy ($\tilde{h}$) over arc section is shown in Fig. 1 for Re = 10, Ro = 1, $\tilde{u}_*$ = 1 and Q values of 0.1 (solid lines) and 0.5 (dashed lines). In this regime a solution exists only for a narrowing arc ($\lambda < 0$); in the first case $\lambda = -0.6$, in the second $\lambda = -0.25$.

Profiles of pressure $\tilde{p}$ and axial velocity $\tilde{u}$ at Re = 10, Ro = 10^{-1}, Q = 1, $\tilde{u}_*$ = 1 are shown in Fig. 2. In this case the pressure changes in an unusual manner: two minima exist — one on the axis, the second in the region of the arc boundary, with the second pressure minimum being deeper. To explain this effect, Fig. 2 also shows the following integral quantities:

$$F(\eta) = -\frac{1}{\mathrm{Ro}^2}\int_\eta^1 \frac{\tilde{\Gamma}^2}{\eta^3}\,d\eta,\quad B(\eta) = \int_\eta^1 [(\tilde{v} - \lambda\eta\tilde{u})\tilde{v}' - \lambda\tilde{u}\tilde{v}]\,d\eta,$$

$$C(\eta) = \int_\eta^1 \frac{\tilde{\varkappa}\tilde{\varkappa}'}{\eta^2}\,d\eta,\quad \tilde{p}(\eta) = \tilde{p}(1) + C(\eta) + F(\eta) + B(\eta).$$

It is evident that in the arc boundary zone the function B(η) has a minimum. This is because in this region the changes in axial and radial velocity are large because of abrupt expansion of the arc. In this regime λ = 1 and reverse flows exist in the arc, which is clearly evident from the axial velocity profile, which changes sign. In this case the enthalpy profile has a minimum on the axis (Fig. 3, solid lines). This is due to transfer of gas flows with a lower temperature by the counterflow from regions lying further down the flow.

The radial velocity $\tilde{v}$ in the central region is negative (Fig. 3), after which, not reaching the minimum pressure zone, the quantity v increases abruptly. The flow clearly is divided

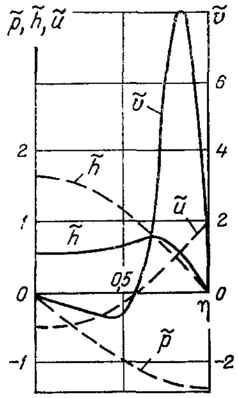

Fig. 3

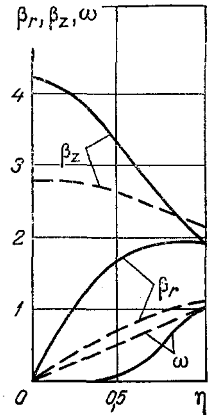

Fig. 4

Fig. 3. Pressure, enthalpy, and radial and axial velocity component profiles. Solid lines, Ro = 0.1, $\lambda = 1$; dashes, Ro = 1, $\lambda = 0.5$.

Fig. 4. Change in electrical field intensity and angular velocity (ω) over arc section. Solid lines Ro = 0.1, $\lambda = 1$; dashes, Ro = 1, $\lambda = 0.5$.

into two regions: an internal one in which the radial velocity is quite low and directed toward the center, and an external one in which the pressure minimum and temperature maximum exist, and the positive radial velocity components are large. Figure 4 shows the changes in the quantities $\omega=\tilde{\Gamma}/\eta$, β_z and β_r along the arc radius. In the axial region the ω values are low, so that we can consider the flow therein practically untwisted. The radial electric field intensity component β_r at the point $\eta = 0.8$ has a maximum.

Figures 3-4 show the characteristics of the electric arc (dashed lines) for the same conditions but with Ro = 1 and in this case $\lambda = 0.5$. Hence it can be concluded that the degree of torsion has a strong influence on the characteristics of an electric arc in a turbulent flow.

In conclusion we will note that the existence of two pressure minima has been observed in turbulence chambers in the absence of an electric arc [5]. This can apparently be explained by stable maintenance of solid particles introduced into the turbulence chamber in some orbit or even several orbits. The latter has been confirmed by experimental studies [2], with a flow containing smoke particles injected into the chamber.

NOTATION

u, axial velocity component; v, radial velocity component; $\Gamma=v_\varphi r$, circulation; v_φ, tangential velocity component; ρ, plasma density; μ, dynamic viscosity; λ_t, thermal conductivity; c_p, specific heat at constant pressure; σ, plasma electrical conductivity; μ_e, magnetic permittivity; E_z, E_r, electric field intensity components along axis z and radius r, respectively; I, total current; B_φ, electric arc magnetic field; $\varkappa$, electric current function; Γ_0, circulation at electric arc boundary; $Ro = u_0R_0/\Gamma_0$, Rossby number; $Re = \rho u_0 R_0/\mu$, Reynolds number; Pr, Prandtl number; Pe = RePr, Peclet number.

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