GAS-VORTEX STABILIZATION OF A JET IN THE NEAR-AXIS ZONE OF A PLASMA REACTOR

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Using the model of turbulent transfer in the field of mass forces, the problem of development of a plasma jet in the near-axis zone of a vortex chamber is solved. The ratio of the maximal tangential velocity to the longitudinal velocity in the jet is shown to have a major influence on gasdynamic plasma confinement. The effects of nonisothermicity and heterogeneity of the flow are much smaller. The available experimental data verify the results obtained.

It is well known [1-3] that flow rotation is an effective means of stabilizing plasma jets and flames. It is widely used in designing plasma generators and vortex-type furnaces. Experiments demonstrate that, with vortex stabilization, the gasdynamic structure of the flow has a major influence on the spatial stability of an arc column and on its characteristics.

Recently, ever closer attention has been given to the problem of gas-vortex stabilization of strongly heated flows [4-9]. These investigations outlined the conditions under which stable confinement of a plasma jet is observed in the vicinity of the axis. The basic characteristic geometric and flow rate parameters, governing the stabilization of a jet when its mixing with a peripheral rotating flow is minimal, are found.

Such a process of jet localization in the near-axis region may be elucidated on the basis of considering a stability mechanism in rotating flows. One of the examples of instability development is the formation of Taylor–Goertler vortexes between rotating coaxial cylinders. Another example of stabilization, observed experimentally, is the propagation of a heated near-axis jet in a vortex gas flow [4-7]. Available experimental data on the turbulence structure in rotating flows [2, 10, 11] established a marked decrease in velocity fluctuations in the regions where turbulent exchange is suppressed. Therefore, jet localization in the near-axis region will be affected by flow laminarization in the mixing layer under the action of the field of mass forces.

The conditions of formation of such regions in twisted flows are known by now [2, 12, 13]. They ensue from the principle of flow stability in the field of mass forces formulated by Rayleigh. In conformity with the above principle, turbulence is suppressed under the condition where $\partial\Gamma/\partial r > 0$ and $\partial\rho/\partial r > 0$. If the circulation and density derivatives reverse their sign along the radius, the turbulent transfer in such zones will be enhanced.

Thus, the mechanism of plasma confinement on the axis of the vortex reactor is affected by two principal factors, viz., by suppression of turbulent exchange due to centripetal forces and due to a density gradient across the radius. Study [7] has determined experimentally the contribution of each of the above factors during stabilization of various-density jets in the vortex chamber.

However, devising reliable methods of calculating the development of jets with gas-vortex stabilization faces a number of fundamental difficulties. First of all, a sufficiently rigorous theory, describing the effect of mass forces on turbulence, is up till now lacking. The available empirical relationships require experimental substantiation for specific conditions. Besides, the process on the whole is affected strongly by flow limitation, characteristic of flow interaction in a vortex chamber. The problem becomes especially complicated when consideration is given to strongly nonisothermal rotating jets, with which the current study deals.

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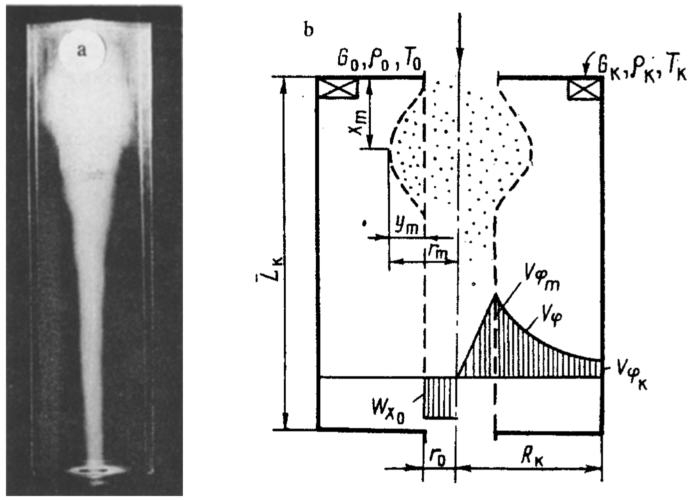

Fig. 1. Development of plasma jet in a vortex reactor (a) and the flow diagram in a plasma reactor (b).

In theoretically describing such complex phenomena, and especially in setting up engineering methods of calculation, it is justifiable to employ the simplest models of turbulent transfer that would account for the principal factors and at the same time give good agreement with experiment. A similar transfer model, worked out earlier, made it possible to describe friction and heat transfer for a wide class of twisted flows, namely, for those in curvilinear channels [14], for swirled tube flows [15], and for vortex semiinfinite jets [16]. The present study has extended this model to jet development with vortex stabilization in nonisothermal conditions. The study aims at establishing quantitative relations between the aerodynamics of a vortex gas flow and the stabilization mode of a heated gas jet.

1. Law of Near-Axis Jet Expansion in the Field of Mass Forces. The flow pattern of a plasma jet with vortex stabilization is fairly intricate. Two characteristic regions are seen on the photograph of a plasma cord (Fig. 1a). Immediately behind the spot of injection of the plasma jet into the vortex chamber, the plasma jet expands intensely, and a peculiar "barrel" forms. Thereafter, the jet diameter decreases due to gasdynamic compression, and further on it does not change along the height of the vortex chamber.

Figure 1b shows a diagram of the flow considered. A gas jet with mass flow rate G_0, temperature T_0, and density ρ_0 is injected axially into a vortex chamber of radius R_{ch} and height L_{ch}. The initial radius of the injected jet r_0 is taken equal to the size of the diaphragm on the opposite end face. The jet is stabilized by supplying to the periphery a swirled gas flow G_{ch} with temperature T_{ch} and density ρ_{ch}. The circumferential velocity on the periphery $V_{\varphi ch}$ and, correspondingly, the circulation $\Gamma_{ch} = V_{\varphi ch}R_{ch}$ are assumed specified, and the tangential Reynolds number is obtained as $Re_{\varphi ch} = \rho_{ch}\Gamma_{ch}/\mu_{ch}$.

Let us adopt the following assumptions. The tangential velocity in the near-axis jet varies linearly over the radius, from zero on the axis to a maximal value on the boundary of its mixing with the peripheral flow (V_φ/r = const). Circulation from the mixing boundary to the side wall of the chamber is unchanged. The axial velocity of individual gas moles in turbulent motion is governed by the mean flow rate velocity at the entry of the near-axis jet to the vortex chamber and remains unvarying along the chamber axis.

We should point out that the adopted assumptions are confirmed by the results of measuring the aerodynamics of vortex chambers with axial injection [2, 5-7, 10]. Besides, we will consider the flow as unaffected by the boundary layers forming on the end surfaces. Such an approximation is rather crude, since the effect of the boundary layers on flow formation in the chamber may in some cases be determining [2]. However, calculations with allowance for end face flows should subsequently present no difficulties.

The gas is assumed ideal, and compressibility effects are disregarded. For simplicity, we take the temperature or concentration profile in the mixing layer to vary by a linear law, and the gas temperature beyond the jet to be constant and equal to the temperature of the peripheral flow T_{ch} at the chamber entrance.

In the analysis we resort to a physical mode of transfer in the field of mass forces worked out for curvilinear and twisted flows [14-16]. Let a turbulent formation (a turbulent mole) be ejected from the boundary of the plasma jet into the external cold flow with a certain initial velocity equal to the root-mean-square value of the radial component of the fluctuating velocity of the turbulent flow $u'_r = (\overline{u'^2_r})^{1/2}$. Of the forces acting on the turbulent mole, we take into account only mass and pressure forces and neglect the effects of viscous friction of the mole on the surrounding gas. Under such conditions, the equation of gas mole motion in the radial direction is written as

$$\rho_0 \frac{du'_r}{dt} = f'_m - \frac{dp}{dr}, \tag{1}$$

where $f_m = \rho_0 \cdot V^2_{\varphi 0}/r - f_0$ is the mass forces composed of the centrifugal component and the force f_0 that gives rise to the fluctuating velocity in the absence of mass forces; and $dp/dr = \rho V^2_\varphi/r$ is the radial pressure gradient.

On substitution and rearrangement with a view to the condition of conservation of the mole circulation in its oscillatory motion, Eq. (1) may be written in the form [14]

$$u'_r \frac{\partial u_r}{\partial y} = -ky + f_0/\rho_0, \tag{2}$$

where

$$k = 2\frac{V_\varphi}{r^2}\frac{\partial (V_\varphi r)}{\partial r} + \frac{1}{\rho}\frac{\partial \rho}{\partial r}\frac{V^2_\varphi}{r}. \tag{3}$$

Integrating Eq. (2) at k = const yields

$$u'^2_r - u'^2_{r_0} = -ky^2, \tag{4}$$

where u'_{r0} is the radial fluctuation of the velocity in the absence of mass forces. For a spatial boundary layer, it may be represented using the theory of mixing length as

$$u'_{r_0} = l_0\left[\left(\frac{\partial W_x}{\partial r}\right)^2 + \left(\frac{1}{r}\frac{\partial \Gamma}{\partial r}\right)^2\right]^{1/2}. \tag{5}$$

On substituting Eq. (5) into Eq. (4) we obtain an expression for velocity fluctuation with the mass forces

$$u'_r = l_0\left[\left(\frac{\partial W_x}{\partial r}\right)^2 + \left(\frac{1}{r}\frac{\partial \Gamma}{\partial r}\right)^2\right]^{1/2}\sqrt{1-\left(\frac{y}{l_0}\right)^2 \mathrm{Ri}}, \tag{6}$$

where

$$\mathrm{Ri} = \frac{k}{(\partial W_x/\partial r)^2 + (1/r\cdot\partial\Gamma/\partial r)^2} = \frac{2\frac{V_\varphi}{r^2}\frac{\partial \Gamma}{\partial r} + \frac{1}{\rho}\frac{\partial \rho}{\partial r}\frac{V^2_\varphi}{r}}{(\partial W_x/\partial r)^2 + (1/r\cdot\partial\Gamma/\partial r)^2} \tag{7}$$

is the Richardson number.

The solution of relation (6) simultaneously with Eq. (7) makes it possible to find the dependence of the fluctuating velocity on the level of centrifugal and buoyant forces in the propagation of a jet with vortex stabilization and to completely calculate the jet development in the vortex chamber.

We first find the maximal diameter of the plasma "barrel" being formed. Evidently, the maximal expansion of the jet will be attained when the radial fluctuation goes to zero, that is, $u'_r = 0$. Then relation (6) gives

$$y_m = \frac{l_{0_m}}{\sqrt{\mathrm{Ri}}}. \tag{8}$$

As in the theory of free turbulence, the mixing length may be assumed to be proportional to the longitudinal coordinate, i.e., $l_0 = C_0 x$. Then its value for the section $x = x_m$ is defined as

$$l_{0_m} = C_0 x_m, \tag{9}$$

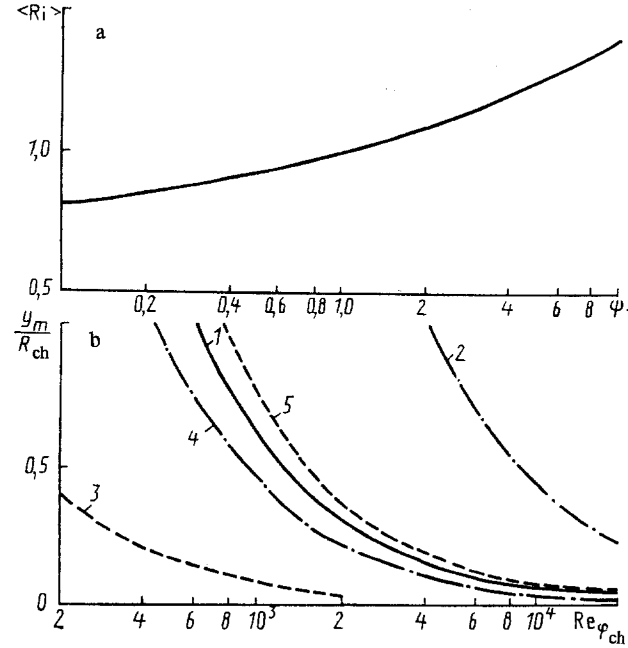

Fig. 2. Effect of the nonisothermicity factor on the integral value of the Richardson number (a) and the expansion law of variable-density jets in the field of mass forces (b), D_{ch} = 0.1 m, r_0 = 0.02 m; G_0 = idem = 10^{-3} kg/sec: 1) ψ = 1; 2) ψ = 10; 3) ψ = 0.1, W_{x0} = idem; 4) G_0 = 10^{-4} kg/sec, ψ = 10; 5) G_0 = 10^{-2} kg/sec, ψ = 0.1.

where C_0 is the turbulence constant, and the coordinate x is reckoned from the chamber entrance.

The maximal expansion of the jet in the radial direction may be presented in the form

$$y_m = \frac{C_0 x_m}{\sqrt{\mathrm{Ri}}}, \tag{10}$$

whereas the largest diameter of the plasma "barrel" is predicted as

$$d_m = 2\,(r_0 + y_m).$$

Let us derive the expansion law for the injected jet on the initial section of its development, where the entrance "barrel" forms. To this end, we represent Eq. (1) as

$$W_{x_0}^2 \frac{\partial^2 y}{\partial x^2} + ky = f_0/\rho_0, \tag{11}$$

where W_{x0} is the axial velocity of the fluctuating mole, equal to the mean flow rate velocity of the jet at the chamber entrance.

The solution of Eq. (11) has the form

$$y = C_1 \frac{W_{x_0}}{\sqrt{k}} \sin\left(\frac{\sqrt{k}}{W_{x_0}} x + C_2\right). \tag{12}$$

Equation (12) with the boundary conditions x = 0, y = 0, x = x_m, y = y_m, and dy/dx = 0 is written as

$$y = y_m \sin\left(\frac{\sqrt{k}}{W_{x_0}} x\right) = C_0 \frac{\pi W_{x_0}}{2\sqrt{k}\sqrt{\mathrm{Ri}}} \sin\left(\frac{\sqrt{k}}{W_{x_0}} x\right). \tag{13}$$

The coordinate x_m, at which the maximal expansion of the jet is attained, can be found from the following relationship:

$$x_m = W_{x_0} \frac{\pi}{2\sqrt{k}}. \tag{14}$$

Thus, obtained relations (13) and (14) allow a complete computation of the boundary of the gas or plasma jet with vortex stabilization. It follows from the equations that the jet boundary changes by a sinusoidal law, and the expansion process is determined by the Richardson number and the complex k, which is an Ri number component.

Let us derive the expression for the Richardson number with a quasisolid law of rotation in the near-axis region. The temperature profile in this zone is also assumed linear

$$\frac{T - T_{ch}}{T_0 - T_{ch}} = 1 - \xi,$$

where $\xi = r/r_m$ and $r_m = r_0 + y$ is the radius of the mixing boundary of the jet. At small expansions of the jet, $y < r_0$, the relative coordinate may be written as $\xi = r/r_0$. The quantities T_0 and T_{ch} are the temperatures on the jet axis and in the chamber.

The density distribution across the mixing layer thickness is written as follows:

$$\rho/\rho_0 = T_0/T = \frac{\psi}{\psi - \xi(\psi - 1)}, \tag{15}$$

where $\psi = T_0/T_{ch}$ is the temperature factor.

Then, given that $\partial W_x/\partial r << 1/r \cdot \Gamma/\partial r$, we have the expression for the Richardson number in the near-axis zone

$$\mathrm{Ri} = 1 + \frac{1}{4}\,\frac{(\psi - 1)\xi}{\psi - \xi(\psi - 1)}. \tag{16}$$

The Ri number varies along the jet radius. Obviously, the jet expansion is influenced by a certain mean value of this parameter

$$\langle \mathrm{Ri} \rangle = \int_0^1 \mathrm{Ri}\, d\xi = 1 + \frac{1}{4}\left(\frac{\psi}{\psi - 1} \ln \psi - 1\right). \tag{17}$$

For isothermal flow ($\psi = 1$), $\langle \mathrm{Ri} \rangle = 1$ in the zone of quasisolid rotation, which lies within the values Ri = 1/24-2 [13, 17-19], at which disturbances in the field of mass forces are suppressed.

As follows from Eq. (17), the mean Richardson number $\langle \mathrm{Ri} \rangle$ is a function of the nonisothermicity factor ψ stipulated by buoyancy effects in the flow with density stratification in a radial direction. Figure 2a shows the results of calculating the Richardson number from Eq. (17) as a function of the temperature factor ψ. Evidently, with rising jet temperature the value of $\langle \mathrm{Ri} \rangle$ increases, so that a positive density gradient along the radius must lead to an additional turbulence suppression. A change in the sign of the density gradient ($\psi < 1$) weakens the stabilization processes. It also follows from Fig. 2a that a quite weak influence of the buoyancy forces on the integral value of the Richardson number is predicted. Thus, heating of the near-axis jet up to T_0 = 3000 K (at T_{ch} = 300 and ψ = 10) causes an increase in $\langle \mathrm{Ri} \rangle$ by 40%. A still lesser influence is expected for the injection of heavy gases along the axis (at ψ = 0.1, $\langle \mathrm{Ri} \rangle$ decreases by about 20%). From simultaneously solving Eqs. (13), (14), and (17), we obtain:

the maximal expansion of the jet

$$\frac{y_m}{r_0} = \frac{C_0 \pi}{4}\left[1 + \frac{1}{4}\left(\frac{\psi}{\psi - 1} \ln \psi - 1\right)\right]^{-1} \frac{W_{x_0}}{V_{\varphi m}}; \tag{18}$$

the longitudinal coordinate of this maximum

$$\frac{x_m}{r_0} = \frac{\pi}{4}\left[1 + \frac{1}{4}\left(\frac{\psi}{\psi - 1} \ln \psi - 1\right)\right]^{-1/2} \frac{W_{x_0}}{V_{\varphi m}} \tag{19}$$

and the trajectory of the outer boundary of the jet

$$\frac{y}{r_0} = \frac{C_0 \pi}{4}\left[1 + \frac{1}{4}\left(\frac{\psi}{\psi - 1} \ln \psi - 1\right)\right]^{-1} \times \sin\left[2\sqrt{1 + \frac{1}{4}\left(\frac{\psi}{\psi - 1} \ln \psi - 1\right)}\ \frac{V_{\varphi m} x}{W_{x_0} r_0}\right]. \tag{20}$$

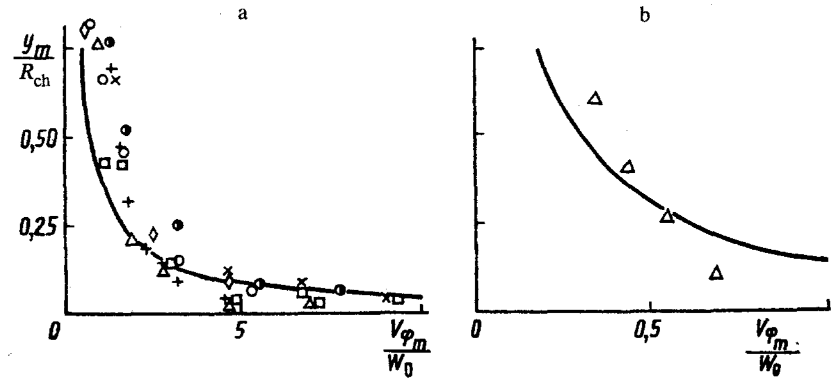

Fig. 3. Expansion law for a near-axis jet: a) isothermal conditions $\psi \approx 1$, dots denote experiment [5], curve denotes calculation from Eq. (18); b) injection of a plasma jet, T_0 = 5500 K, dots denote experiments [7], curve denotes calculations from Eq. (18).

It follows from relations (18)-(20) that the expansion law for the jet with vortex stabilization is specified by two parameters, viz., by the ratio of the longitudinal velocity in the jet to the maximal circumferential velocity $W_{x0}/V_{\varphi m}$ and by the nonisothermicity factor ψ. These equations permit us to completely calculate the jet expansion and analyze the centrifugal and density stratification effects on dynamic and thermal characteristics of jets with vortex stabilization.

2. Discussion of Results. Comparison to Experimental Data. We will write expression (18) for y_m as a function of the tangential peripheral Reynolds number $Re_{\varphi h} = \rho_{ch} V_{\varphi ch} \cdot R_{ch}/\mu_{ch}$ and of the mass flow rate of the jet $G_0 = \pi \rho_0 W_{x0} r_0^2$, which are used most frequently in the processing of experimental data:

$$\frac{y_m}{R_{ch}} = \frac{C_0}{4} \frac{\psi}{1 + \frac{1}{4}\left(\frac{\psi}{\psi - 1} \ln \psi - 1\right)} \frac{G_0}{Re_{\varphi ch} R_{ch} \mu_{ch}}. \tag{21}$$

The calculated results for expansion of various-density jets are shown in Fig. 2b. Lines 1-3 are obtained for a flow rate of the near-axis jet of $G_0 = 10^{-3}$ kg/sec; here line 1 corresponds to isothermal conditions (ψ = 1), line 2 to injection of a hot jet (ψ = 10), and line 3 to injection of a cold jet or of a jet of greater molecular mass into a light peripheral flow (ψ = 0.1). Clearly, with an increase in the tangential Reynolds number, i.e., with a rise in the rotation rate of the stabilizing flow, the maximal transverse dimension of the "barrel" y_m/R_{ch} reduces appreciably. Stabilization of a light gas jet (curve 2) is achieved at Reynolds numbers considerably larger than in an isothermal jet and, conversely, a heavy gas jet (curve 3) begins to be confined at relatively low rates of rotation. At first glance, this contradicts the mechanism of density stratification of the flow where a positive density gradient leads to flow stabilization, and a negative density gradient to flow destabilization. However, of primary importance in this case is an increase in the longitudinal velocity in the light gas jet, as compared to the isothermal flow, due to its density reduction, provided the flow rates of the jets are identical. Accordingly, when the heavy gas is injected, its longitudinal velocity will decrease by $1/\psi$ times.

If we carry out similar calculations at the same jet velocities W_{x0}, having correspondingly changed the jet flow rates, then, as we might expect, the jet of the light gas (curve 4, ψ = 10) is stabilized faster than that of the heavy gas (curve 5). We note that the specific features indicated in Fig. 2b are verified qualitatively by experimental data [5, 7].

Relations (18)-(21) derived above contain one empirical quantity C_0, which is the turbulence constant. Its value for free mixing layers [20] and for near-wall rotating jets [16] lies within the range $C_0 \approx$ 0.09-0.14. In our case, for jets developing in vortex chambers, this value turned out to be C_0 = 2.2. Such a marked variation may have different causes, the main of them being, to our mind, the effect of end face flows, the use, for a linear scale, of the initial jet radius r_0 rather than of the mixing layer width, neglect of the longitudinal velocity shear in the jet, etc.

Figure 3a compares the experimental and calculated data on the maximal jet expansion in quasi-isothermal conditions. In the experimental data, y_m corresponds to the thermal diameter of the jet of a weakly heated gas ($T_0 \approx$ 40-60°C) at various initial diameters of the jet over a wide range of its flow rates. Clearly, the experimental data plotted as func-

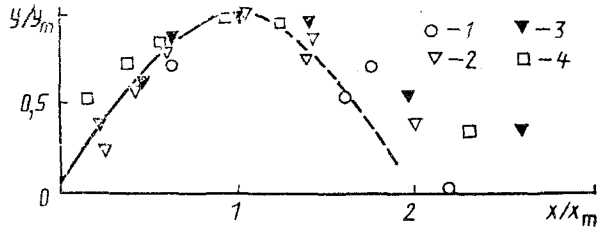

Fig. 4. Trajectory of a plasma jet with vortex stabilization; experiments [7]: 1) $Re_{\varphi ch} = 7.2 \cdot 10^4$; 2) $8.7 \cdot 10^4$; 3) $1.1 \cdot 10^5$; 4) $1.4 \cdot 10^5$; the curve denotes the calculation by Eq. (20).

tions of the ratio of the maximal rotational velocity to the longitudinal velocity are correlated and well consistent with the calculational relation. It is significant that, when $V_{qm}/W_{x0} > 5$, the expansion of the jet is practically unnoticeable and steady stabilization is attained in its near-axis region.

Figure 3b gives a comparison of the calculated and experimental data [7] on the maximal expansion of a jet of low-temperature plasma. The diameter of the plasma reactor is $D_{ch} = 85$ mm, its length $L_k = 300$ mm, $r_0 = 4$ mm, and the diameter of the inlet opening is $d_i = 20$ mm. The bulk temperature of the air plasma at the inlet is $T_0 = 5500$ K, and the temperature factor is $\psi = 20$. The thermal diameter of the jet was determined by microphotometry of plasma column photographs.

As is evident, the model proposed gives results fairly close to the experimental data, the plasma jet stabilization being attained at velocity ratios V_{qm}/W_{x0} smaller than in quasi-isothermal conditions. This is due to the influence of such a significant temperature factor on the process of plasma confinement.

Figure 4 gives in relative form the trajectories of plasma jets on the initial section for various tangential Reynolds numbers. The maximal expansion of the "barrel" y_m and the longitudinal coordinate of this maximum x_m are taken as linear scales. The curve in this figure marks the calculation by Eq. (20). The trajectory of the jet during its formation in the field of mass forces obeys a sinusoidal law, which the model exactly predicts. The experimental data have an appreciable spread and deviate from the calculations in the region of "barrel" compression, where the diameter of the stabilized jet assumes a minimal value, virtually unchanged over the vortex chamber height.

CONCLUSIONS

1. We have performed an analysis of the development of a jet injected into the near-axis zone of a vortex chamber. We have analyzed the mechanism of gasdynamic stabilization of the jet in the field of mass and buoyant forces. A model of the jet expansion in the vortex chamber has been proposed.

2. The main influence on the expansion of the near-axis jet is exerted by the ratio of the maximal circumferential velocity to the mean flow rate value of the axial velocity in the jet. The nonisothermicity factor is of secondary importance.

3. The obtained analytical relations qualitatively adequately describe the experiment. From a comparison with experimental data, we found turbulence constants for a jet with vortex stabilization on the initial flow section.

4. The suggested transfer model disregards the effects of a great number of factors, for example, of end face flows, of radial mixing of the gas in the jet along the chamber height, of viscosity, etc. The task of further investigations is to develop and improve the model with regard to the noted specific features of the complex flow considered.

NOTATION

L_{ch}, R_{ch}, height and radius of the vortex chamber; r_0, radius of its outlet opening; x, y, r, longitudinal and transverse coordinates and running value of the radius; $\xi = r/r_c$, relative coordinate; $r_c = r_0 + y$, radius of the mixing layer of the jet; $V_\varphi r$, running values of tangential and axial velocities and of circulation; $V_{\varphi ch}$, $V_{\varphi m}$, tangential velocity on the peripheral wall of the chamber and its maximal value; W_{x0}, mean flow rate velocity of the near-wall axis; ρ_0, T_0, density and temperature of the wall; ρ_{ch}, T_{ch}, density and temperature of the peripheral stabilizing jets; G_{0m}, G_{ch}, maximal flow rates of the jet and of the peripheral flow; $\psi = T_0/T_{ch}$, nonisothermicity factor; y_m, $r_m = r_0 + y_m$, x_m, maximal transverse expansion of the jet, its maximal radius, and longitudinal coordinate of the maximum; u'_r, pulsatory radial velocity; f_0, f_m, mass forces; k, parameter defined by relation (3); Ri, Richardson number, defined by Eq. (7); ⟨Ri⟩, mean Richardson number, defined by Eq. (17); j_0, C_0, mixing length and turbulence constant; $Re_{\varphi ch} = \rho_{ch} V_{\varphi ch} R_{ch}/\mu_{ch}$, peripheral tangential Reynolds number. Indexes: 0, jet parameters and conditions with no rotation; ch, chamber periphery; m, maximal value.

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