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# An experimental study of the flow stabilization in a channel with a swirled periphery jet

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## Abstract

This paper represents results of experimental study on the coaxial flow mixing in channels with a swirled periphery jet. These experiments were carried out in the long cylindrical tubes and in the vortex chambers with a diaphragmed exit. The main attention was paid to the parameter distribution in the near-axial region of the flow depending on the entrance geometry and flow rate characteristics. The effects of the swirl angle of the periphery jet, a thickness of the edge between coaxial flows, and the concurrency parameter $m = \rho_s w_s/\rho_0 w_0$ on the flow stabilization within the field of centrifugal mass forces were analyzed. A character of stabilizing effect of the flows on the mixing processes was determined by a gas temperature change along the channel's axis and turbulence intensity. Generalizing dependencies were obtained for a relative temperature at the axis both in the swirled and direct flows. Experimental results on the heat flow mixing in vortex chambers are shown here. There are some similarities for transfer processes in the vortex chambers and long tubes. The main difference is that the diaphragmed chamber and boundary layers at the edge walls considerably effect the mixing. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* Cylindrical channel; Vortex chamber; Coaxial flow; Swirled periphery jet; Stabilization of flow; Profiles of velocity and temperature; Turbulence

## 1. Introduction

Gas-swirl stabilization of the flow by a periphery swirled jet is widely used in technique, and chemical engineering to control the heat and mass transfer processes. The jet swirl is also used for the protection of a working surface in power installations and setups, which deal with the high-temperature working media, such as vortex furnaces and burners, aircraft engines, etc. [1–3]. Swirl stabilization of plasma jets is one of the most efficient methods for plasma retaining in the near-axial area in the channels of the low-temperature generators. This methods protects the reactor's walls from a thermal effect of the plasma jet [4,5].

The stabilization process is extremely sensitive to the change of regime and geometrical parameters. Thus, the determination of the boundaries of a stable localization of high-temperature jets is necessary for the prediction of the optimal regime parameters for plasmatrons and plasma-chemical reactors. The main difficulty, arising during the design of the devices with swirl retention of plasma jets or flames, is absence of a reliable date on aerodynamics and heat and mass transfer in these devices.

The problem under consideration is very complicated. A three-dimensional character of the flow is ac-

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**Nomenclature**

| | |
|---|---|
| $c_p$ | specific heat capacity |
| $D$ | diameter of the working section |
| $d$ | diameter of the diaphragm edge cap or of the main stream channel |
| $G$ | flow rate |
| $I_0$ | impulse flux, $I_0 = 2\pi\rho_0 \int_0^{r_0} W_x^2 r \, \mathrm{d}r$ |
| $K$ | integral parameter, $K = I_0 R_c / M_s$ |
| $L$ | length of the cylindrical channel |
| $M_s$ | moment of momentum flux of the peripheral flow, $M_s = 2\pi\rho_s \int_{R_{c-s}}^{R_c} W_x V_\varphi r^2 \, \mathrm{d}r$ |
| $m$ | injection parameter, $m = \rho_s w_s / \rho_0 w_0$ |
| $Re$ | Reynolds number |
| $s$ | slot width |
| $T$ | temperature |
| $t$ | rim thickness |
| $Tu$ | turbulent level (%) |
| $x$ | longitudinal coordinate |
| $x_0$ | length of initial region of the central flow |
| $r$ | radial coordinate |
| $r_{0.1}$ | coordinate of the dimensionless temperature $(T - T_w)/(T_0 - T_w) = 0.1$ |
| $y$ | transverse coordinate from wall |
| $y'$ | distance from maximal value position |
| $y_{0.5}$ | coordinate of the half maximal dimensionless velocities or temperature |
| $W_x$ | longitudinal velocity |
| $V_\varphi$ | swirl velocity |
| $\Gamma$ | circulation, $\Gamma = V_\varphi r$ |
| $\eta$ | dimensionless temperature, $\eta = (T_0 - T_s)/(T_{01} - T_s)$ |
| $\mu$ | dynamic viscosity |
| $\nu$ | kinematic viscosity |
| $\rho$ | density |
| $\varphi$ | swirl angle |
| $\delta_m$ | distance of the maximal velocity or temperature from the wall |
| * | value beyond the edge boundary layer |

*Subscripts*

| | |
|---|---|
| c | vortex chamber |
| in | inside conditions |
| m | maximal value |
| mix | value of complete mixing of co-axial jets |
| 0 | main stream, value on an axis |
| 1 | conditions at initial section |
| s | secondary stream |
| w | at wall |

companied by the impact of a strong field of centrifugal forces on the transfer processes. The flow anisothermic character can affect significantly the flows mixing. This is confirmed by investigations in this field [2,6–8].

The process of gas-dynamic stabilization of a jet in the near-axial area can be explained using the concepts of the stability mechanism in rotating flows. Available experimental data on the turbulence structure in rotating flows [7,9,10] demonstrate and investigate areas with a damping of the turbulent exchange. That is why, the jet localization process, in the near-axial area, will be affected by the flow laminarization in a layer of mixing under the action of the mass forces field.

In general, the formation conditions of these areas in swirled flows are known now [1,7,11,12]. They follow from the principle of the flow stability in the field of mass forces, formulated by Raleigh. According to this principle, the necessary conditions of the turbulence damping are circulation and density distribution over a radius $\partial\Gamma/\partial r > 0$ and $\partial\rho/\partial r > 0$. The intensification of the turbulent transfer will occur with reverse signs of circulation and density gradient.

We would like to notice one more important condition, influencing the processes of jet mixing in swirl flows. The swirl of a peripheral stabilizing jet leads to the gradient increase of the total averaged velocity. According to the existing ideas concerning the mechanism of turbulent energy generation [7,13], this factor must lead to mixing strengthening, deteriorating the thermal insulation of plasma jet from chamber walls.

Thus, three main factors will influence the mechanism of high temperature jets: the damping of the turbulent transfer at the expense of centrifugal forces, buoyancy forces, resulted from the density gradient over a radius, and mixing intensification due to the increase of the total velocity gradient in a swirl flow as well. In works [8,11–14] experimental estimates of each factor contribution during stabilization of jets with different density in vortex chambers were performed.

However, these data cannot be considered as exhaustive ones, because they do not illustrate the variety of swirl flow interaction. The great influence on mixing processes as a whole will be caused by the flow boundedness, characteristic for the flow interaction in a vortex chamber. Boundary layers, forming at the side and front walls, can lead to a cardinal restructuring of the flow. According to experimental data [15,16], a size relation of peripheral and near-axial jets and rim thickness, separating these jets, affect on the flow formation.

The creation of reliable methods for calculation of

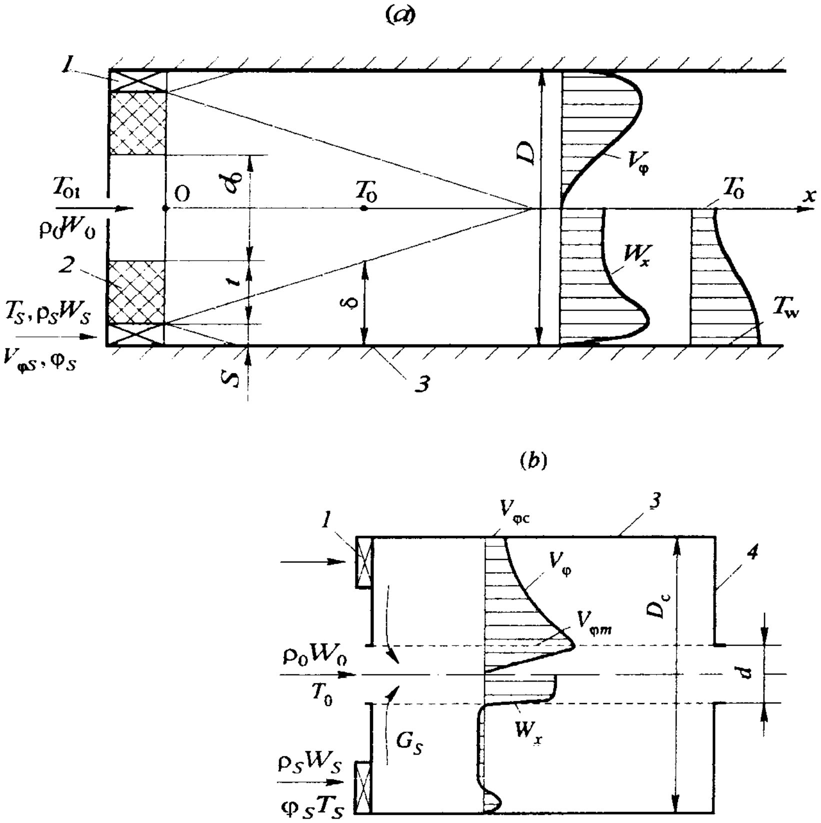

Fig. 1. Studied schemes of mixing of co-axial swirled jets: (a) cylindrical channel, (b) diaphragm vortex chamber. 1—swirler; 2—separation rim; 3—side wall; 4—edge cap.

jet development with gas-swirl stabilization meets some principle difficulties. First of all, at present there is no strict theory, describing the effect of mass forces on turbulence. Available empirical ratios and simple theories need experienced proof for the certain conditions under consideration.

Experimental studies with a direct injection of plasma jets into a channel are complicated by methodological difficulties. The high level of temperatures does not allow to perform fine parameter measurements with good spatial resolution. Thus, the model constructions, illustrating the main features of the physical mechanism of the complex studied process, have a great importance.

The present work is devoted to experimental modeling of swirl jets mixing in channels. Particularly, parameters in the near-axial flow area were studied thoroughly. Two characteristic cases of jets mixing were investigated during experiments. They are most often realized in the various technological arrangements: mixing in long cylindrical channels (Fig. 1(a)) and in swirl diaphragm chambers (Fig. 1(b)). In the first case, the flow is modeled inside a discharge channel of plasmatron and in the second, inside a discharge channel of plasma reactor for various plasma-chemical processes. The main aim of the presented cycle of experimental investigation is the revealing of the total regularities of transfer process in these two kinds of swirl flows as well as the individual peculiarities of structure formation of the flow.

## 2. Mixing of co-axial swirl jets in a tube

Experimental studies were carried out in a cylindrical channel with an inner diameter $D = 46$ mm and length $L/D = 9$ caliber (Fig. 1(a)). The near-wall jet was fed at the inlet to a working section through tangential ring slit with a width $s = 2$ mm. It was swirled inside the slit by spiral ribs with different outlet angles relatively the axial direction.

In some experiments we studied the influence of a rim, separating the flows, on mixing of co-axial flows. The rim thickness, $t$ changed at the expense of variation of the axial jet diameter, $d$, when its relative value became $t/s = 0.15$, 1.5, 4 and 8.

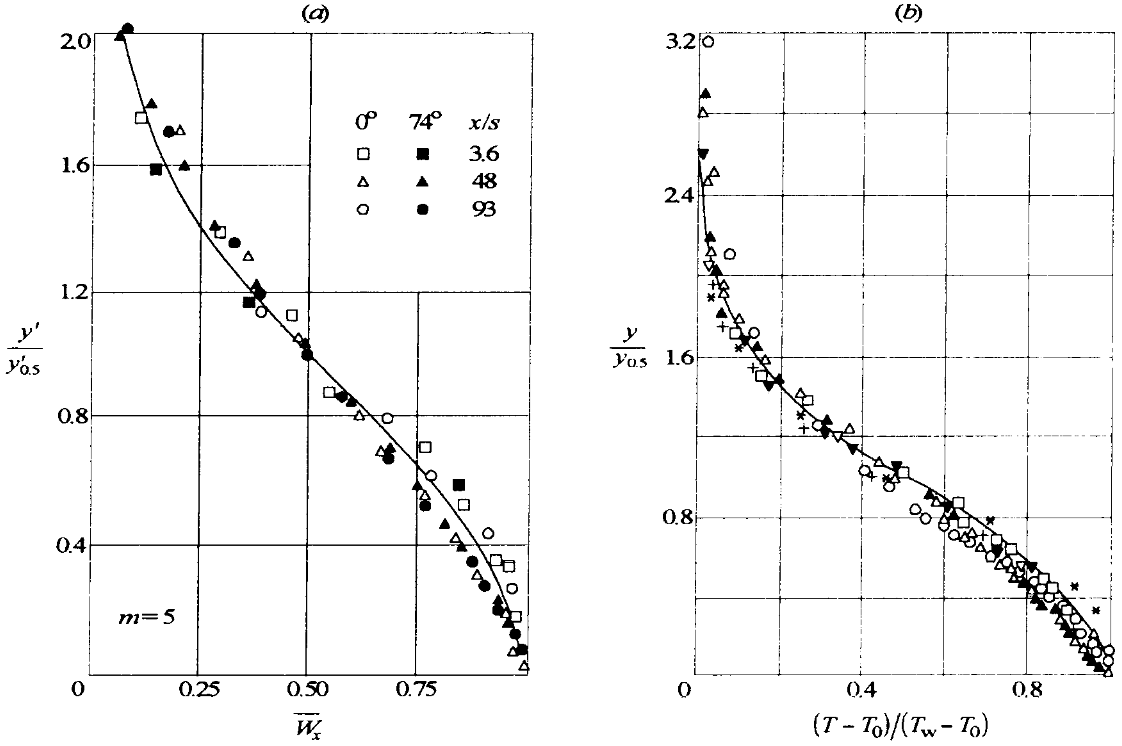

Fig. 2. Profiles of longitudinal velocity (a) and temperature (b) in jet boundary layer. Lines correspond to calculation by formula (1).

Experiments on jets heat mixing were carried out under conditions, close to isothermal ones: one of the flows (central or peripheral one) was heated 60°C relatively another. The main air flow was fed with a velocity $W_0 = 30$–$300$ m/s, the relative parameter of the air injection through the slit was varied in a wide range $m = \rho_s W_s/\rho_0 W_0 = 0.2$–$8$. The measurement of the fields of velocity components, their pulsation and temperature was performed by microprobes. The detailed description of measurement methods and their errors are given in Ref. [17].

The mixing of the peripheral ring jet with the central flow in a tube with high injection parameters has a jet-like character. Profiles of longitudinal and tangential velocity and temperature are described by known jet dependencies. Generalizations of measured radial distributions of longitudinal velocity and temperature, presented in Fig. 2, confirm the above. The line in this figure corresponds to calculation according to Gauss's formula:

$$\bar{W}_x = \bar{V}_\varphi = \bar{T} = \exp\left[-0.693\left(y'/y_{0.5}\right)^2\right] \qquad (1)$$

where $\bar{W}_x = (W_x - W_0)/(W_{xm} - W_0)$, $\bar{V}_\varphi = V_\varphi/V_{\varphi m}$ and $\bar{T} = (T - T_0)/(T_m - T_0)$ are dimensionless velocities and temperatures; $y' = y - \delta_m$; and $y_{0.5}$ is a coordinate of the half maximal velocity or temperature. The universality of the ratio (1) was valid in all studied range of swirl angles, distances from the inlet and injection parameters. The only exception is a behavior of the longitudinal velocity component at low injection parameters ($m < 1$), when near-wall processes start to govern the influence on the flow. Besides these conditions, the flow development in axial direction is affected by the swirl of a peripheral jet, which can result in a significant deformation of the velocity profiles. In detail this problem is considered in Refs. [17,18].

Radial distribution of a circulation channel $\Gamma = V_\varphi r$, flow swirl angle ($\varphi = \mathrm{arctg}(V_\varphi/W_x)$) and moment of momentum flux as well are described by the jet regularities (1). This conclusion, obtained in work [19] is important for the development of theoretical models on jet-like flows mixing.

The temperature alteration along the axial length is one of parameters, characterizing the intensity of flow mixing. The temperature value on an axis is usually expressed in dimensionless form $\eta = (T_0 - T_{\mathrm{mix}})/(T_{01} - T_{\mathrm{mix}})$, where $T_0$ and $T_{01}$ are the flow temperatures on the axis in the current cross-sec-

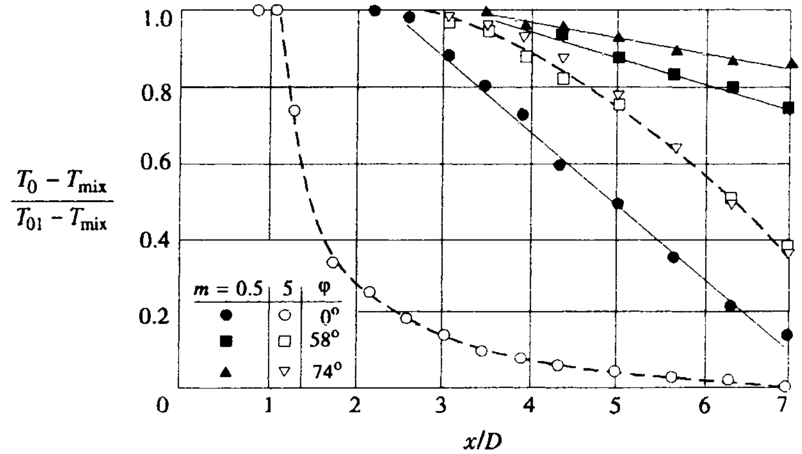

Fig. 3. Influence of peripheral flow swirl on the temperature along a channel axis.

tion and in the channel inlet, $T_{\text{mix}} = (G_0 C_{p_0} T_{01} + G_s c_{p_s} T_s)/(G_0 + G_s) c_{p_{\text{mix}}}$ is the temperature of complete mixing, $G_0$, $c_{p_0}$ and $G_s$, $c_{p_s}$ are the flow rate and specific heat capacity of the central and peripheral flows, correspondingly.

Experimental data on temperature alteration along the channel axis for different swirl angles of the peripheral flow with thin separation rim ($t/s = 0.15$) are presented in Fig. 3. Dimensionless temperature, equal to 1, corresponds to the initial region of the central jet, and temperature, equal to 0, corresponds to the area of complete mixing. It is obvious from the figure that the length of the initial region is small for non-swirled peripheral jet (2 caliber for $m = 0.5$ and 1 caliber for $m = 5$). The temperature alteration at the main region of the flow depends upon the injection parameter and swirl angle. The jets mixing is more intensive for $m = 5$ than for $m = 0.5$ as for swirled so for non-swirled jets. The peripheral flow swirl leads to a reduction of mixing processes. According to Fig. 3, it can be considerable.

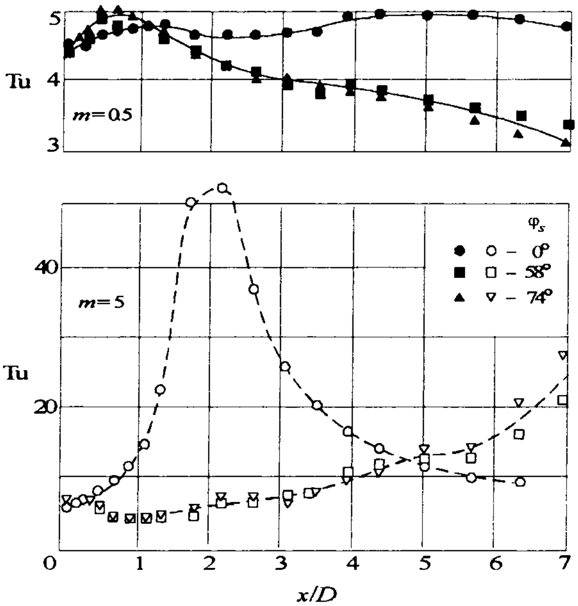

Fig. 4. Turbulence degree of a jet with peripheral swirl in the near-axial area.

This character of $T_0$ change along the axis is explained by the effect of centrifugal forces. The swirl of the peripheral flow creates positive circulation gradient over the radius, which leads to the damping of velocity pulsation and flow stabilization in the near-axial area. This is confirmed by the measurements of the turbulence degree along the length in the near-axial area. Results of these measurements are presented in Fig. 4. The turbulence degree is determined as $Tu = \sqrt{\bar{W}_0'^2}/W_0$ where $W_0$ and $\bar{W}_0'^2$ are the averaged and root-mean-square velocity pulsation at the axis in the studied cross-section. It is clear from Fig. 4 that the swirl of the peripheral flow decreases the turbulence degree in the near-axial area. Nearly complete degeneration of initial turbulence is observed for low injection parameters ($m = 0.5$) and swirl angles $\varphi_s = 58$–$74°$.

The turbulence change along the channel axis has a complex character for high injection parameters ($m = 5$). The turbulence maximum is reached in the joining area of jets boundary layers. There is no such extremum for the swirled peripheral flow within the length of the region.

The thickness of the separation rim, $t/s$, an important parameter, has influence on the mixing process. At the first stage we studied the influence of the rim size on the regularity of temperature alteration along the axis without rotation. These data are presented in Fig. 5. An increase of the rim thickness, separating two

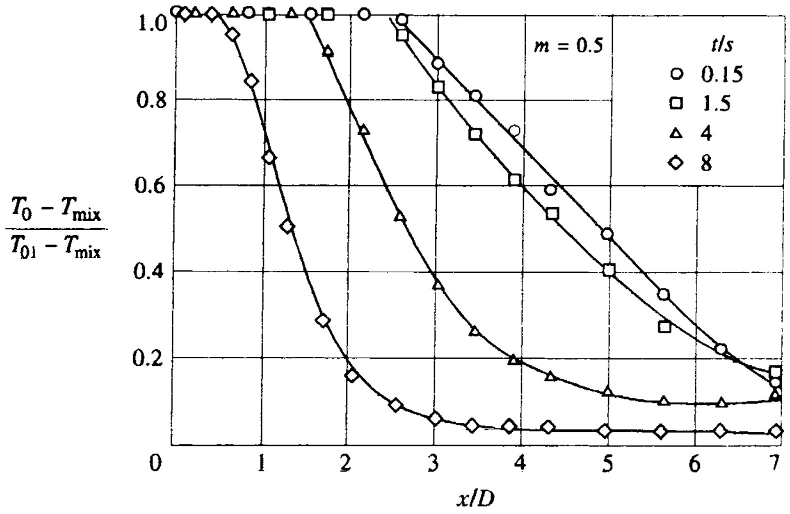

Fig. 5. Influence of separation rim thickness on temperature alteration along the axis without swirl.

non-swirled flows, promotes their mixing and, correspondingly, the decrease of the length of potential flow zone in the near-axis area. Thus, the decrease of $t/s$ from 0.15 to 8 reduces the relative length of potential core from 2.5 to 0.5, in so doing the temperature along the axis decreases drastically, almost reaching the value of complete mixing.

A change of the separation rim thickness causes a significant alteration of the pulsation pattern of the flow. This can be observed in Fig. 6, where the data on the turbulence intensity along the axis are presented for different values of $t/s$. If for the thin rim the turbulence degree stayed nearly constant and relatively low $Tu \approx 4\%$, then for the thick rim ($t/s = 8$) it reached the value $Tu \approx 28\%$, and maximum in $Tu$ distribution shifted to the inlet cross-section with a growth of the rim thickness.

The intensification of mixing processes with a rim thickening is caused by the formation of a swirl trace behind the separation rim, which leads to the additional flow turbulization. This conclusion is confirmed by experimental data of [20] on the mixing of non-swirled bounded jets.

In the swirled flow a temperature decrease along the axis at a rim thickening occurs not so drastically as in the non-swirled flow (Fig. 7). The swirl of the periph-

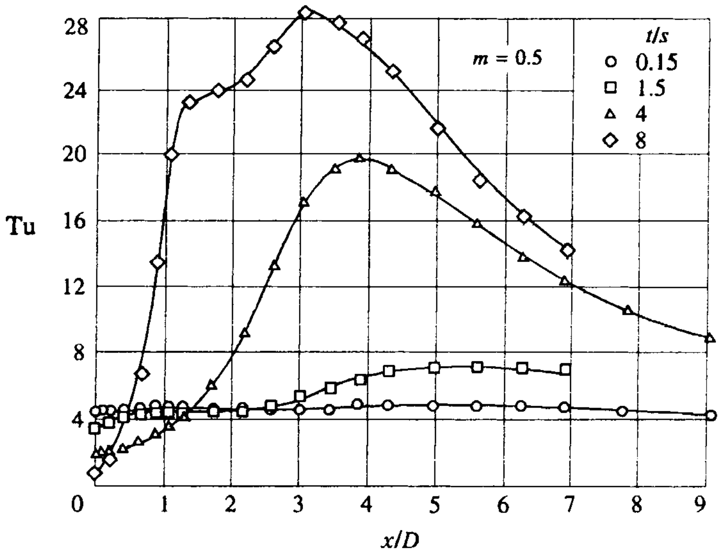

Fig. 6. Influence of separation rim thickness on turbulence intensity, when mixing non-swirled flows.

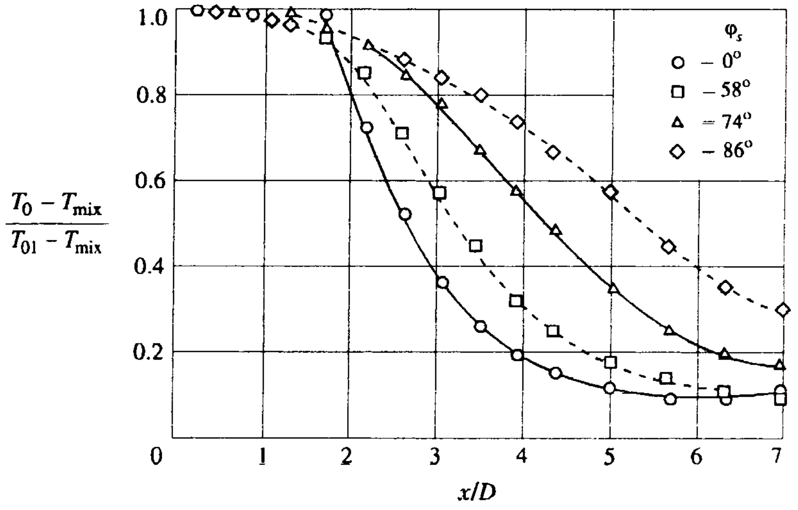

Fig. 7. Temperature distribution along the axis with thick rim $t/s = 4$ and peripheral flow swirl.

eral flow leads to the intensive damping of the turbulent pulsation in the near-axial area. This mixing peculiarity of coaxial flows with a swirl is shown in Fig. 8. There you can see the turbulence alteration along a channel length for different swirl angles at the inlet and constant rim size $t/s = 4$. As for the case with a sharp rim (Fig. 4), the flow turbulence degree decreases with a raise of the swirl angle, and its maximum shifts from the initial cross-section.

Thus, an increase of the separation rim thickness and flow swirl have an alternative impact on mixing processes and turbulence in the near-axial area. Moreover, in some cases the influence of these factors may be commensurable and mutually compensating. This conclusion is confirmed by Fig. 9, where experimental points for the wide rim ($t/s = 4$) and swirl of the peripheral flow ($\varphi_s = 74°$) are relatively close to the data for the sharp rim and swirl absence.

Besides the view in Figs. 3, 5, 7 and 9, the temperature on the axis can be plotted in the dimensionless form: $\eta = (T_0 - T_s)/(T_{01} - T_s)$. Value $\eta$ is similar to the efficiency of the near-wall gas cooling, but it also reflects a change in the gas temperature along the channel's axis.

For different swirl angles of a periphery jet and varying width of the separating edge, experimental data on the $\eta$ parameter can be generalized by the following empirical dependency:

$$\eta = \left[1 + 0.1 Re_{s,\Delta x} \Big/ \left(Re_{0,r}\frac{r_0}{D}\right)^{1.25}\right]^{-0.8} \qquad (2)$$

where $Re_{s,\Delta x} = \rho_s W_s(x - x_0)/\mu_s$; $Re_{0,r} = (\rho_0 W_0 r_0/\mu_0)(\mu_0/\mu_s)$, $x_0$ is a length of initial region of the central flow. The relationship (2) by its structure is similar to calculation dependencies for the efficiency of

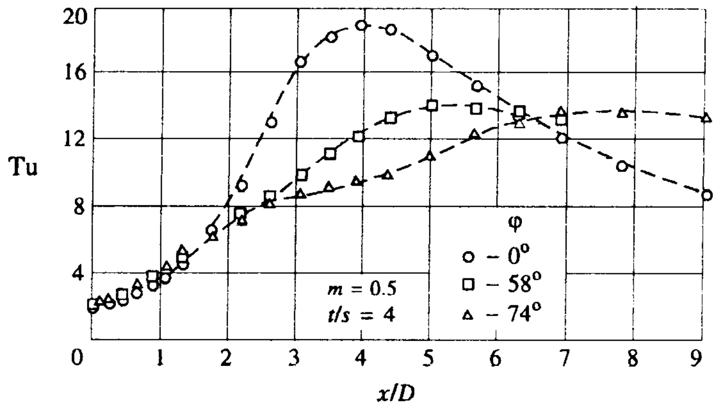

Fig. 8. Influence of swirl angle on turbulence intensity in the near-axial area with thick separation rim.

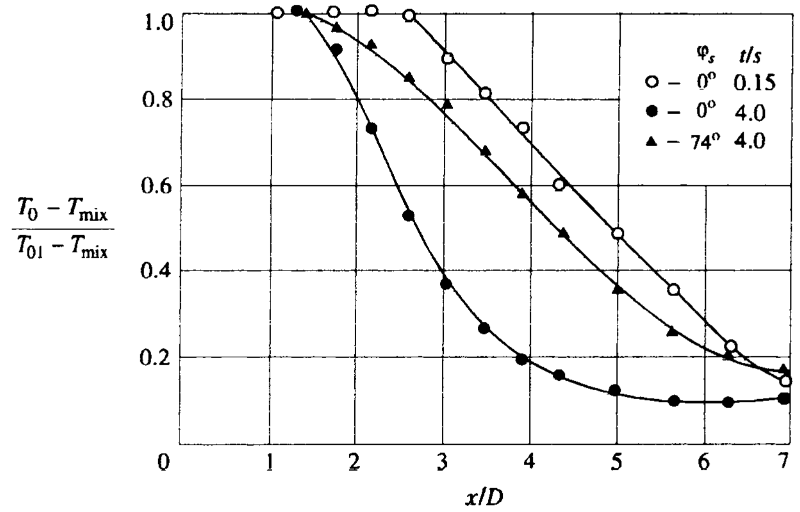

Fig. 9. Temperature on channel axis with varying swirl angle and separation rim thickness for constant flow rate of near-axial and peripheral flows.

the near-wall gas cooling [5]. Moreover, it includes the same determining parameters, which are used in temperature calculations for the adiabatic wall in the gas cooling.

The comparison of calculation according to this formula with experimental data is presented in Fig. 10. You can see a good correspondence between the experiment and calculation.

For the case of non-swirled peripheral jet, the temperature along the axis of the central flow was satisfactorily described by the dependence similar Eq. (2), but with an other value coefficient in this formula

$$\eta = \left[1 + 0.25 Re_{s,\Delta x} \Big/ \left(Re_{0,r}\frac{r_0}{D}\right)^{1.25}\right]^{-0.8} \qquad (3)$$

## 3. Jets stabilization in swirl chambers

The experimental study of stabilization of near-axial jets was carried out in a vortex chamber with a diameter of $D_c = 100$ mm and the length of $L_c = 150$ mm (Fig. 1(b)). The peripheral flow of cold gas was swirled by means of guide apparatuses, whose slits were situ-

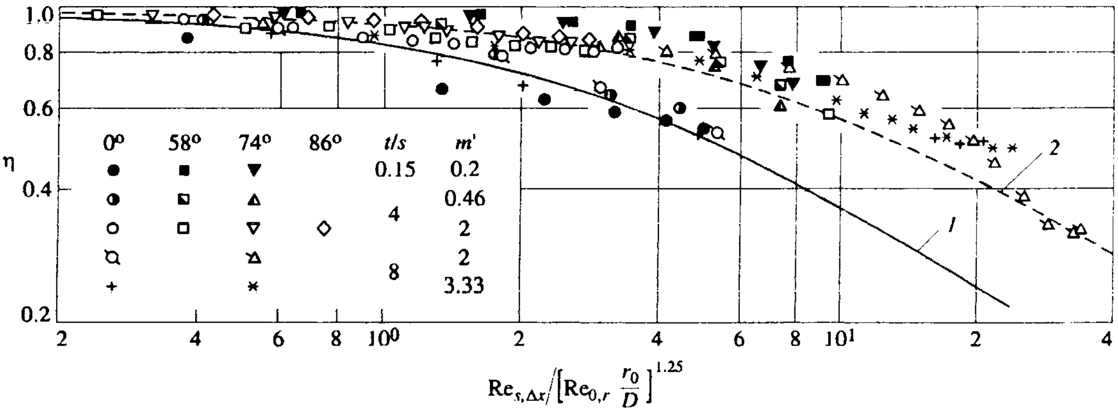

Fig. 10. Generalization of experimental data on temperature alteration along the channel axis. 1—calculation by formula (3); 2—calculation by formula (2).

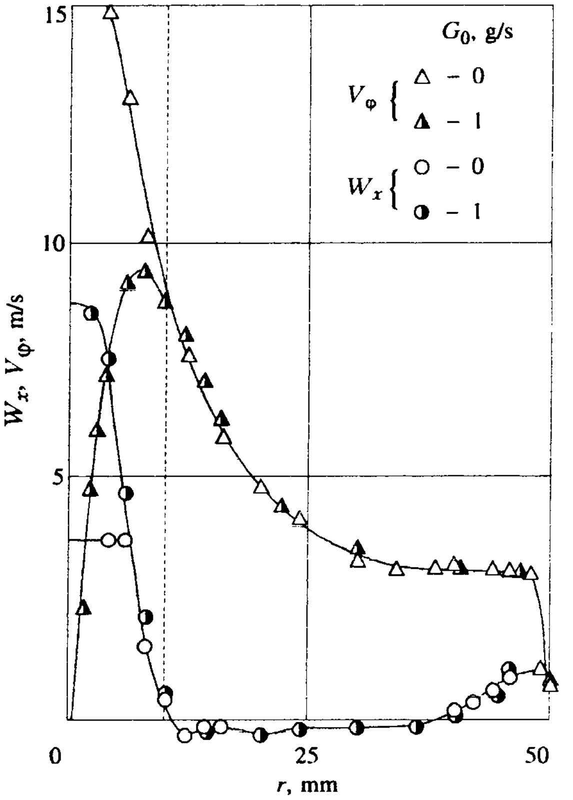

Fig. 11. Profiles of tangential and axial velocities in a vortex chamber with and without near-axial injection.

ated under different angles. The near-axial jet, heated up to 100°C, was injected without swirl with different velocities along the vortex chamber axis. An air from the chamber was ejected through a diaphragm edge cap at the chamber outlet. The flow rate ratio of the peripheral flow and near-axial jet varied in maximally possible limits from 0 to ∞. The tangential Reynolds number at the periphery of the chamber was $Re_{\varphi s} = V_{\varphi s}R_c/\nu = 5 \times 10^3$–$2 \times 10^5$. The detailed description of this setup and measurement methods are presented in [15].

The influence of the near-axial jet injection on radial distributions of tangential and axial velocities is shown in Fig. 11. Let us note the main peculiarities of the vortex chamber aerodynamics in the presence of a near-axial jet. The presence of the injected flow affected only in an area bounded by the diaphragm size ($r < r_0$). At the periphery the experimental data with or without injection nearly coincide, as for the circular, so for the axial velocity components. The input of non-swirled jet to the near-axial area causes a significant deceleration of the rotation motion, and the longitudinal velocity component at the axis increases with a raise of injection.

Experimental studies showed that a flow in the vortex chamber with injection can be considered as a quasi-one-dimensional, i.e., radial distributions of tangential velocity do not change over the chamber height, and the injection affects the longitudinal velocity only in the near-axial area. Thus, the main fea-

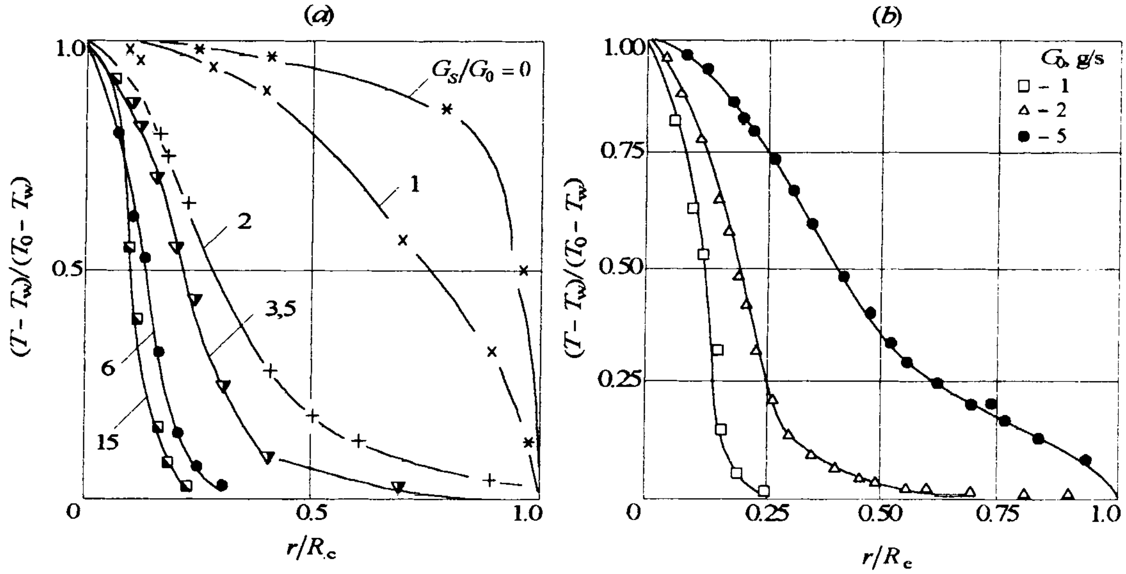

Fig. 12. Temperature distribution over a radius of a vortex chamber: (a) $G_0 = 1$ g/s; (b) $Re_{\varphi c} = 2.75 \times 10^4$.

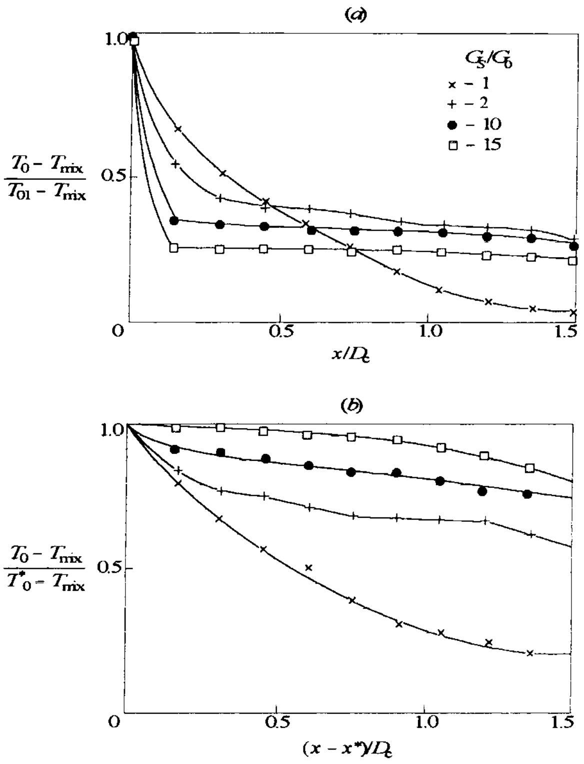

Fig. 13. Maximal temperature alteration over the chamber height.

tures of the flow pattern in common vortex chambers without injection maintain for the case of injection [7].

Temperature profiles over the radius of the vortex chamber for different flow rates of the peripheral jet are shown in Fig. 12(a). Gas injection along the axis without peripheral flow ($G_s/G_0 = 0$) results in a quick jet mixing in the chamber volume, and even in initial cross-sections the temperature does not change over the radius. Temperature gradients in the mixing zone increase with a growth of tangential velocity, and near-axial jet localizes in the narrow near-axial area due to the damping of heat transfer processes.

The flow rate increase of the near-axial jet, with steady parameters of the peripheral flow, leads to more intensive jet expansion (Fig. 12(b)).

Let us analyze the temperature distribution along the axis of the vortex chamber for various cases of near-axial jet interaction with the swirled peripheral flow. Maximal temperature alterations over the chamber height for various tangential Reynolds numbers for the periphery $Re_{\varphi c}$ and constant flow rate of the near-axial jet $G_0 = 10^{-3}$ kg/s are presented in Fig. 13. Experimental data were treated adjusting the temperature of complete mixing for different flow rate ratios.

It is obvious from Fig. 13, that values of relative temperatures at the chamber axis decrease with an increase of rotation intensity of the peripheral flow. At first sight, this contradicts to the impact mechanism of centrifugal forces on the damping of the turbulent transfer in rotating flows. However, analyzing Fig. 13(a), one can see that the main temperature alteration occurs near the chamber inlet, where the flow in the edge $Re_{\varphi c}$ boundary layer can have a considerable effect. Actually, higher the tangential Reynolds number the higher gas flow rate passing over the edge from the periphery to the chamber axis in the radial direction. The flow rate of cold gas in the edge boundary layer may be calculated using ratios from [7].

As it follows from Fig. 13(a), the temperature gradient over the length of the chamber with rotation intensification decreases in the area beyond the edge

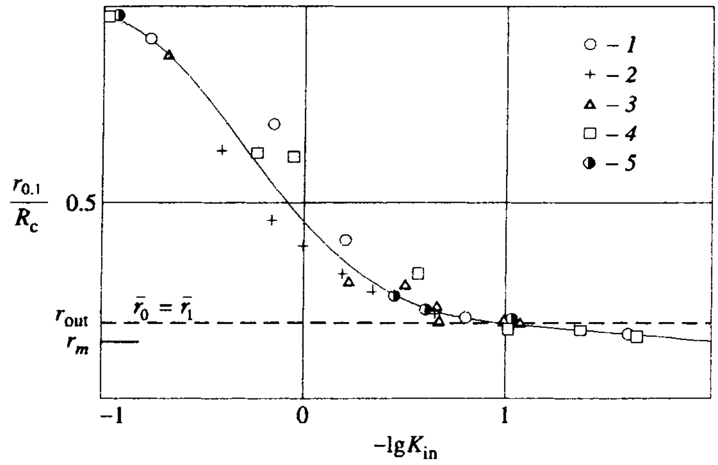

Fig. 14. Heat boundary of a jet in a vortex chamber.

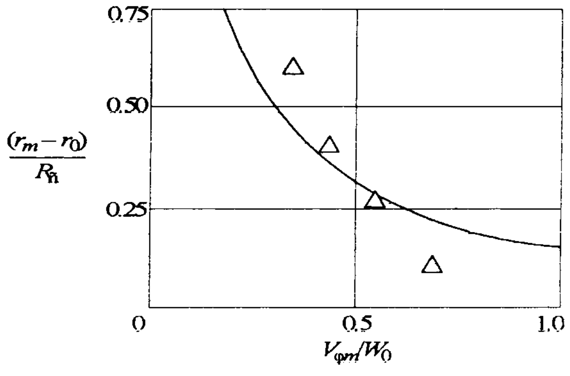

Fig. 15. Expansion regularity of the near-axial plasma jet, $T_0 = 5500$ K.

boundary layer ($x/D_c > 0.15$). This confirms the weakening of mixing processes in the main volume of the chamber at the expense of mass forces.

At the next stage the experimental data of Fig. 13(a), were recalculated to the initial jet temperature. It was equal to the temperature beyond the edge boundary layer. Results of this treatment are presented in Fig. 13(b). Here, the relative temperature is $(T_0 - T_{\mathrm{mix}})/(T_0^* - T_{\mathrm{mix}})$, where $T_0^*$ is the gas temperature at the axis beyond the edge boundary layer. This treatment allowed us to exclude the influence of dilution of the jet by the edge gas flow, and analyze the impact of mass forces on turbulent mixing in the main volume of the chamber. It is obvious that, on the contrary to the data in Fig. 13(a), the increase flow rate in the peripheral flow leads to the stabilization of the near-axial flow and weakening of convective heat transfer in the vortex chamber.

The generalization of experimental data on jets mixing in vortex chambers was performed with a use of various criteria. One of widely used generalizing criterion is the integral parameter:

$$K = \frac{I_0 R_c}{M_s} = 2\pi\rho_0 \int_0^{r_0} W_x^2 r \, \mathrm{d}r \times R_c \Big/ \left( 2\pi\rho_s \int_{R_{c-s}}^{R_c} W_x V_\varphi r^2 \, \mathrm{d}r \right) \quad (4)$$

representing the ratio of the impulse flux of the near-axial jet to the moment of momentum flux of the peripheral stabilizing flow [4]. Calculating $K$ parameter according to the conditions at the chamber inlet, we will obtain:

$$K_{\mathrm{in}} = \frac{\rho_0 W_{x0}^2 F_0}{\rho_s W_{xs} V_{\varphi s} F_s} = \frac{G_0 W_{x0}}{G_s V_{\varphi s}} \quad (5)$$

Experimental data on the heat parameter of a jet, calculated with a use of $K_{\mathrm{in}}$ parameter, are presented in Fig. 14. There, one can see the data for different flow rate ratios and for a constant diameter of an exhaust hole, whose boundary is marked by a dotted line in the figure. It is obvious that in this form experimental results can be generalized easily. Moreover, with a jet heat size approximately equal to the exhaust diameter, the jet stabilization occurs, when parameter $K_{\mathrm{in}} < 0.3$. This corresponds to results of [21]. Experimental results of this work demonstrated that the regime of the minimal jet mixing with the peripheral swirled flow in a nondiaphragm channel occurs, when $K$ parameter is in a range of $0.6 \geq K_{\mathrm{in}} \geq 0.15$.

The experimentally determined critical value of the swirl parameter $K_{\mathrm{in}} \leq 0.3$, when stabilization of the near-axial jet is achieved, is proved by calculation analysis of [8]. While mixing very non-isothermal or density heterogeneous flows, the ratio of tangential velocity at the boundary of the near-axial jet to the longitudinal velocity component $V_{\varphi m}/W_{x0}$ was the most suitable stabilization parameter. This is confirmed by the correlation of experimental and calculation data on the maximal expansion of the plasma jet in the vortex chamber, presented in Fig. 15. The jet stabilization is obtained there at $V_{\varphi\mathrm{m}}/W_{x0} \geq 1$. According to [15] this regime under isothermal conditions is achieved at $V_{\varphi\mathrm{m}}/W_{x0} \geq 5$. This manifests a significant influence of the jet heating on the damping process of turbulence mixing in the swirl flow.

## 4. Conclusion

According to the experimental research of the flow stabilization process in the near-axial region of the swirled flows, we can conclude the following:

1. The swirling of a peripheral jet significantly weakens its mixing with the main flow. With a rise in the swirling angle, the turbulence intensity at the channel's axis decreases. The suppression effects increase with a rise of the jet injection parameter. They are shown especially bright when the flow passes through the diaphragmed vortex chamber.
2. It was analyzed the joined effect of the edge width, separating the flows, and intensity of the peripheral jet swirling. It is shown that a rise in the edge width intensifies mixing, and jet swirling weakens it. Finally, varying these parameters, we can obtain mutual exclusion of these parameter effect on the mixing process.
3. It was established that the profiles of temperature and velocity components in the mixing layer are similar and can be described by the known jet dependencies.
4. For the case of the main flow mixing with the

swirled and not-swirled jets, a temperature change along the axis of a channel is described by the relationships similar to those for the heat efficiency of gas cooling at an adiabatic wall. Expression (2) for the swirled jet differs from corresponding formula (3) for the jet without swirling only by the constant coefficient.

5. The processes of mixing suppression in the vortex diaphragmed chambers have some similarities with the flow in a tube with a swirled jet. The main distinctive features of flow mixing in the vortex chamber are the strong effect of the diaphragmed chamber and boundary layers at the edge walls.
6. Experimental data on the heat boundary of the near-axial flow can be generalized by the use of integral parameter (4) and (5). It was determined value ($K < 0.3$), when the regimes of minimum mixing in the vortex chambers can be achieved. Under strongly non-isothermal conditions ($T_0/T_s \gg 1$), the ratio of a circular velocity component to longitudinal component at the boundary of the near-axial flow is the most suitable for the description of the flow stabilization boundary.

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