TURBULENT JET IN A CHANNEL SUBJECTED TO ARCHIMEDES FORCES

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Fundamental regularities of the flow being formed during blowing of a heated jet in a vertical circular channel are found experimentally. An integral method is proposed for computation of such a flow. A comparison of the computation results with experiment is presented.

Turbulent nonisothermal jets in channels are often encountered in practice. The characteristic features of such flows is the formation of reverse current zones and a high turbulence level. Experimental investigations [1, 2] show that Archimedes forces exert substantial influence on the jet flow structure in a plane channel and the heat elimination to the wall. Investigation of such a flow is of interest for the axisymmetric case also.

The influence of Archimedes forces on turbulent jet development in an axisymmetric channel was studied [3-5]. Attempts were made in [3, 4] to take account of the influence of the Archimedes forces by using approximate dependences. Let us note, however, that these dependences are obtained without taking account of the stream restriction as for a free submerged jet. Presented in Fig. 1b are experimental data from [5] on the change in velocity along the jet axis (the open circles are for the isothermal case and the dark points for the heated jet). On the basis of a comparison between these data as well as with a computation for the isothermal case (line 1) and for a free submerged nonisothermal jet (line 2) the authors of this paper conclude that the Archimedes forces occurring during heating of the jet in the channel will result in more rapid damping of the velocity on the axis. However, as computations performed by the method in [6] for a nonisothermal flow (line 3) showed, in this case not the Archimedes forces result in more rapid damping of the velocity on the axis but the stream nonisothermy does. The Archimedes forces for this flow mode ($Ar_0 \approx 2.5 \cdot 10^{-6}$) are so small that they do not cause a noticeable change in the velocity.

Known approaches to a theoretical description of the effect of Archimedes forces on jet flow in channels are quite approximate and do not permit description of the whole flow field [3, 4, 7].

Experiments were conducted on an installation whose working section was a circular vertical channel of 3.25-m height and 0.63-m diameter (Fig. 1a). The installation was in a box with a T = 293 K air temperature. The channel wall was from stainless steel 2 mm thick plate. A hot air jet was delivered along the channel axis through a nozzle from above. The air was heated to T = 293-423 K by using electrical heaters. Nozzles having a Vitoshinskii profile with a minimal section diameter of d_0 = 13.5 and 50 mm were used in the tests. The mass flow of air was regulated in the 4-12 g/sec range during the experiments. The air velocity in the minimal section was here u_0 = 25-80 m/sec for the 13.5-mm nozzle, and u_0 = 2-10 m/sec for the other nozzle. The velocity was checked by a thermoanemometer. The nonuniformity of the velocity u_0 profile for the 13.5-mm nozzle did not exceed 1% while the degree of turbulence in the minimal section of this nozzle was 0.7% on the average. The average velocity u_0 profile for the other nozzle can be represented approximately by a function of the form $u/u_m = (1 - y/r_0)^{1/8}$, and the degree of turbulence in the minimal section did not exceed 3-5%.

The averaged values of the gas velocity and temperature within the channel were measured in the experiments, as were also the temperatures of the outer wall surface. To measure the velocity, as in [1, 2], a phase-inverting thermoanemometer [8] was used with temperature compensation that permits execution of measurements in highly turbulent flows with reverse current zones, and a special four-thread sensor [2]. The total errors of the measurements did not exceed the following quantities: 4% for u and 0.5% for T for a P = 0.95 fiducial probability.

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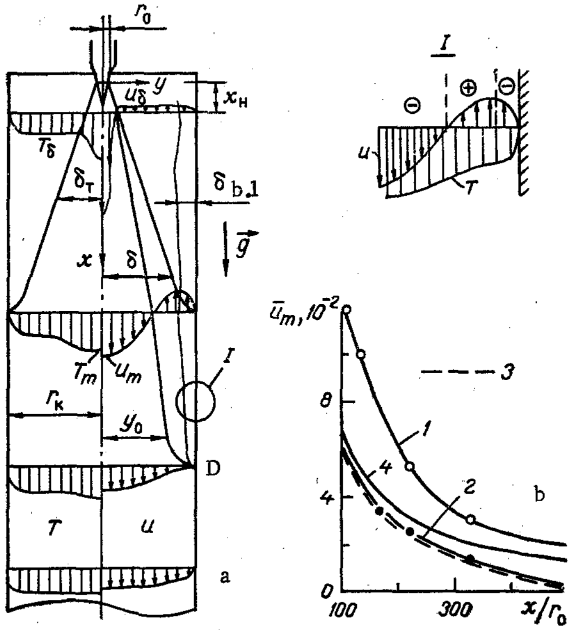

Fig. 1. Flow diagram (a) and velocity change on the channel axis u_m along the x coordinate (b): b) u_0 = 183 m/sec; r_k = 0.25 m; r_0 = 0.003 m; 1) computation for $\vartheta = 1$; 2 and 3) computation without and with taking account of the Archimedes forces for ϑ = 2.4; 4) computation of a free submerged jet with Archimedes forces taken into account for ϑ = 2.4; points are experiment [4] (open circles ϑ =1; dark circles ϑ = 2.4).

Analysis of the experiment results showed that the flow being formed in the range of blowing velocities and nozzle sizes under investigation was independent of Re_0. The influence of the Archimedes forces for the flow modes examined turned out to be substantial for $Ar_0 = g\beta(T_0 - T_{w0})d_0/u_0^2 \geqslant 0.0005$. Let us note that the Archimedes forces for free submerged jets exert substantial influence on the flow configuration for Ar_0 = 0.001 [9].

When the Archimedes forces are small, the nature of the gas temperature change near the channel wall T_δ and the wall temperature T_w are similar to the velocity distribution u_δ: the maximum of T_δ and T_w correspond approximately to the maximum of u_δ. As the number Ar increases an essential reconstruction of the flow configuration occurs under the effect of the Archimedes forces.

Presented in Figs. 2 and 3 are certain results of an experimental investigation of the flow configuration in a channel for different values of the velocity and temperature of a jet injected through a r_0 = 25 mm nozzle. Shown in Figs. 2a and 3a are velocity profiles in different channel section and lines indicating the flow direction, constructed from the results of thermoanemometer measurements. Shown on the left of the channel axis are profiles for the isothermal case and on the right for a heated jet. As is seen from Fig. 2 the relative velocity $\bar{u}_m$ on the jet axis damps more rapidly for the parameter value Ar_0 = 0.0025, the recirculation zone becomes shorter, and the velocity level $\bar{u}_\delta$ in this zone diminishes as compared with the isothermal case. Under the effect of the Archimedes forces the velocity u_m drops to zero and a reverse flow directed upward is formed on the axis. Let us note that for an opposite direction of the Archimedes force effect, in contrast to the case under consideration they result in elongation of the recirculation zone and magnification of the velocity level in this zone [1] (the wall rather than the jet, as in this paper, was heated in [1]).

The formation of a "dropping" free-convective flow directed opposite to the forced stream is possible in the recirculation domain for high Archimedes numbers (Fig. 3) near the relatively cold walls. The velocity profile measured near the wall for such a case is presented in pos. I. The nature of the change in the temperatures T_δ and T_w for high values of Ar_0 is determined mainly by the free convection: the highest wall temperature is observed above where the hottest gas is collected.

The long range of a free submerged jet with negative buoyancy [10], defined as the distance to a point on the jet axis where the velocity is zero, is marked by a vertical bar in

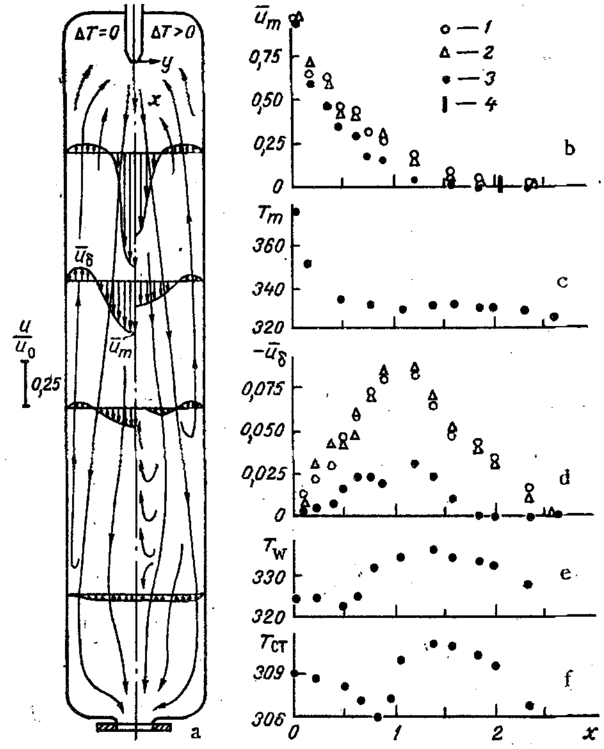

Fig. 2. Flow configuration in a channel under the essential influence of Archimedes forces (experimental data): a) flow pattern; b and c) change in gas velocity and temperature on channel axis; d and e) change in gas velocity and temperature at 2 cm distance from channel wall: 1) u_0 = 3.7 m/sec, ϑ = 1; 2) u_0 = 4.8 m/sec, ϑ = 1; 3) u_0 = 6.6 m/sec, ϑ = 378/309, Ar_0 = 0.0025; 4) long-range free submerged jet with negative buoyancy for Ar_0 = 0.0025, ϑ = 378/309, T_m, T_δ, T_w, K; x, m.

Figs. 2b and 3b. It is seen that the long range of a jet in a channel is less than the long range of a free jet, which can be explained by the influence of the walls cooling the gas. A heated gas moving upward along "cold" walls diminishes the velocity resulting in reconstruction of the whole flow and reduction of the velocity on the axis from the condition of conservation of the mass flow rate in channel transverse sections.

For a theoretical description of the flow under consideration with Archimedes forces in a channel with relatively large elongation, it is expedient, in our opinion, to use boundary layer methods. One such method for the analysis of a nonisothermal jet in a channel without taking account of the Archimedes forces is described in detail in [6]. The boundary layer approximation in the flows under consideration is satisfied sufficiently well as experiments show.

Let us limit ourselves to a consideration of channels with a high degree of expansion r_k/r_0. In this case the jet initial section of extent x_H (see Fig. 1a) has small dimensions as compared with the domain under consideration and can be computed by known turbulent jet theory methods without taking account of the wall influence. An approximate computation of the main flow domain can be made on the basis of solving the integral equations of mass flow rate conservation

$$2\pi\left(\int\limits_0^\delta \rho u y dy + \int\limits_\delta^{r_\text{к}} \rho u y dy\right) = 2\pi \int\limits_0^{r_0} \rho_0 u_0 y dy; \tag{1}$$

of momentum

$$\frac{d}{dx}\left[2\pi\left(\int\limits_0^\delta \rho u^2 y dy + \int\limits_\delta^{r_\text{к}} \rho u^2 y dy\right) + \pi r_\text{к}^2 P\right] = \pm 2\pi g \int\limits_0^{r_\text{к}} \rho\beta (T - T_\infty) y dy; \tag{2}$$

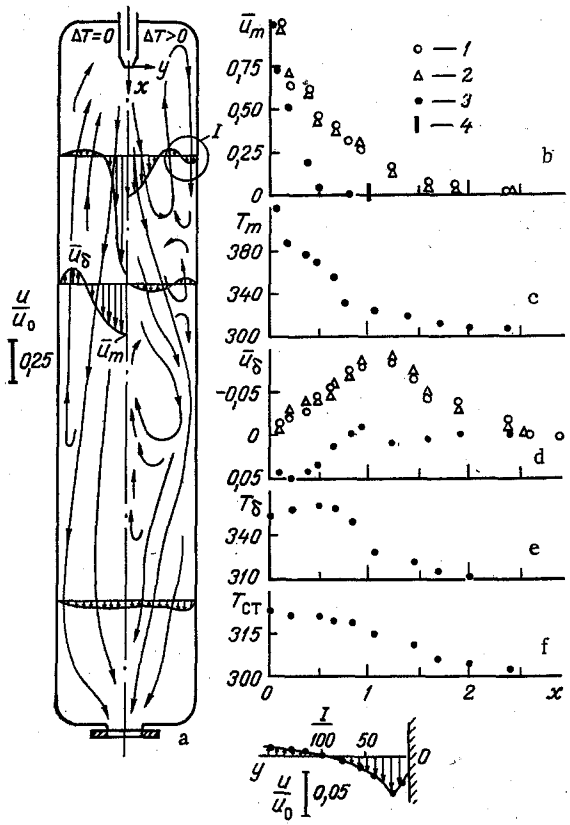

Fig. 3. Flow configuration in a channel under the essential influence of Archimedes forces (experimental data): values a–f the same as in Fig. 2; 1) u_0 = 3.7 m/sec, ϑ = 1; 2) u_0 = 4.8 m/sec, ϑ = 1; 3) u_0 = 4 m/sec, ϑ = 423/325, Ar_0 = 0.0094; 4) long-range free submerged jet with negative buoyancy for Ar_0 = 0.0094, ϑ = 423/325, y, mm.

of energy

$$2\pi\left(\int_0^\delta c_p\rho uTydy+\int_\delta^{r_\text{к}}c_p\rho uTydy+r_\text{к}\int_0^x q_\text{ст}dx\right)=2\pi\int_0^{r_0}c_{p_0}\rho_0u_0T_0ydy \tag{3}$$

and the equation of state

$$f(P,\ \rho,\ T)=0. \tag{4}$$

The term in the right side of (2) expresses the momentum received by the jet from the action of the Archimedes forces and the direction of Archimedes force action (see Fig. 1, pos. I) must be taken into account for this evaluation. In Eq. (2) and henceforth, the upper sign corresponds to the case when the directions of jet propagation and the acceleration of gravity are opposite, and the lower to coincident directions.

Using the method of polynomial approximation of the tangential stress and turbulent heat flux profiles [12], similarly to [6, 11], velocity and temperature profiles can be obtained in transverse sections of the jet

$$\frac{u-u_\delta}{u_m-u_\delta}=A_1/A_2; \tag{5}$$

$$\frac{T}{T_m}=\vartheta_m^{-f(\eta_\text{т})}, \tag{6}$$

as can also the law of velocity and temperature variation along the channel axis:

$$\frac{du_m}{dx}=-\frac{2(u_m-u_\delta)\rho_m(\nu+\nu_\text{т})+\left[\dfrac{\partial P}{\partial x}\mp\rho_m g\beta(T_m-T_\infty)\right]\delta^2A_2}{\rho_m u_m\delta^2A_2}; \tag{7}$$

$$\frac{dT_m}{dx} = -\frac{24\,(\nu/\mathrm{Pr} + \nu_\text{т}/\mathrm{Pr}_\text{т})\, T_m \ln \vartheta_m}{u_m \delta_\text{т}^2}, \tag{8}$$

$$A_1 = \int_0^\eta \vartheta_m^{-f(\eta_\text{т})}\,\eta\,(1-\eta)^2\,d\eta,\quad A_2 = \int_0^1 \vartheta_m^{-f(\eta_\text{т})}\,\eta\,(1-\eta)^2\,d\eta,$$

$$\vartheta_m = T_m/T_\delta,\ f(\eta_\text{т}) = 6\eta_\text{т}^2 - 8\eta_\text{т}^3 + 3\eta_\text{т}^4,\ \eta = y/\delta,\ \eta_\text{т} = y/\delta_\text{т}.$$

Here ν_T is the coefficient of turbulent viscosity for which the following expression, analogous to the known Prandtl formula, is used

$$\nu_\text{т} = \varkappa\delta\,(u_m - u_\delta)\,F_1F_2,$$

where F_1 and F_2 are corrections taking account of the influence of nonisothermy and the Archimedes forces. The expressions for these corrections have the form [11]

$$F_1 = \left[f\,\frac{\rho_m + \rho_\delta}{2\rho_m}\right]^{0,8},\quad F_2 = \left|1 \pm J\beta g\,\frac{\delta^2(T_m - T_\delta)}{\delta_\text{т}(u_m - u_\delta)^2}\right|.$$

The quantities δ and δ_T are interrelated by the following dependence [12]

$$\delta_\text{т} = \delta/\sqrt{\mathrm{Pr}_\text{т}}. \tag{9}$$

We use the Kutateladze–Leont'ev boundary-layer method [13] to determine the local heat flux in the channel wall q_w that is in (3). For the flow under consideration (Fig. 1a), the near-wall boundary layer is developed from the point D, the parameters at the outer boundary of the boundary layer are found from (1)-(9). The heat flux distribution in the channel wall is determined from the formula

$$q_w = \mathrm{St}_0\psi_s\rho_\delta c_{p_\delta} u_\delta\,(T_\delta - T_w), \tag{10}$$

where $\psi_s \approx \prod_i (\psi_s)_i$ is the relative heat-transfer law taking account of the influence of different factors on the heat transfer. For the case under consideration, such factors as the nonisothermy $(\psi_s)_T$, the external turbulence $(\psi_s)_{Tu}$, and the buoyancy force $(\psi_s)_{Ar}$ are of interest. To take account of the influence of stream nonisothermy the following dependence is obtained in [13]: $(\psi_s)_T = [2/(\sqrt{T_w/T_\delta} + 1)]^2$. An essential intensification of the heat elimination as compared with a computation for $(\psi_s)_{Tu} = 1$ is remarked for an investigation of convective heat transfer at the wall of a channel with a sudden expansion, and which the authors associate with the influence of external turbulence in [14]. On the basis of [14] is it possible to obtain

$$(\psi_s)_{Tu} \approx 1 + 80/\sqrt{\mathrm{Re}_\text{т}^{**}}.$$

The regularities of Archimedes force influence on heat transfer in turbulized streams have not yet been studied, however, it is difficult to expect that they will be influential to the same extent as is external turbulence. Consequently, in a first approximation it is possible to take $(\psi_s)_{Ar} = 1$.

We use the known method of elementary balances [15] which can be used to compute wall heating and to take account of heat transfer from the outside of the wall to the environment, in order to determine the wall temperature T_w from the gas side.

The system of ten equations (1)-(10) obtained has eleven unknowns u, T, u_m, T_m, u_δ, T_δ, δ, δ_T, ρ, P, q_w. Let us note that when the jet reaches the channel walls the quantity δ is known and equals r_k. According to known experimental data [14] it is possible to take $P = P_0 =$ const in the flow domain where $\delta < r_k$. Taking account of the above, the system of equations is closed. The algorithm developed for the numerical solution of this system was realized in the form of a program for the SM-4 minicomputer in the language FORTRAN-IV. The solution was by successive approximations. The machine time expenditure to compute one flow mode was approximately 20 min for the nonisothermal case and 3 min for the isothermal case.

Comparison of the computation results with experiment showed that the computation method elucidated describes the flow in a channel with satisfactory accuracy for relatively small Archimedes number (see Fig. 4). It is seen from Fig. 4a that for $Ar_0 = 2\cdot10^{-5}$, exactly as the experiment (dark points), the computation (continuous line) indicates negligible influence of the Archimedes forces on the flow configuration as compared with the isothermal case (dashed line and open circles). For $Ar_0 = 0.0025$ (Fig. 4b), just as the experiment, the computation yields more rapid damping of the velocity $\bar{u}_m$ and diminution of the velocity $\bar{u}_\delta$ near

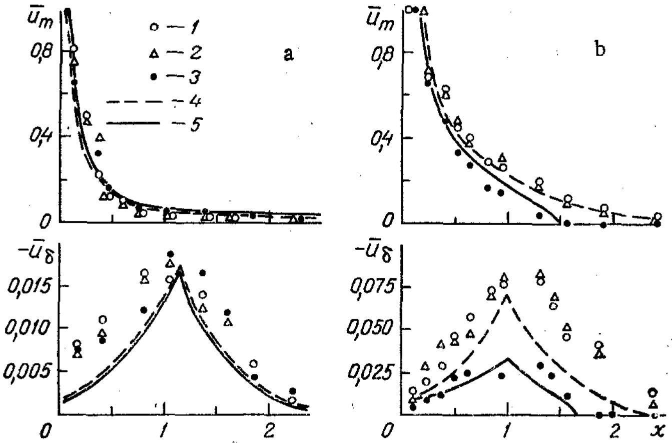

Fig. 4. Comparison of computation results with experiment (lines are the computation and points are the experiment): a) r_0 = 6.75 mm; 1) u_0 = 44.4 m/sec, ϑ = 1; 2) u_0 = 31.8 m/sec, ϑ = 1; 3) u_0 = 45.5 m/sec, ϑ = 423/327, $Ar_0 = 2 \cdot 10^{-5}$; 4) Ar_0 = 0; 5) $Ar_0 = 2 \cdot 10^{5}$; b) r_0 = 25 mm; 1) u_0 = 3.7 m/sec, ϑ = 1; 2) u_0 = 4.8 m/sec, ϑ = 1; 3) u_0 = 6.6 m/sec, ϑ = 378/309, Ar_0 = 0.0025; 4) Ar_0 = 0; 5) Ar_0 = 0.0025.

the wall. The computed values of the jet long range are obtained approximately the same as in experiment. It should be noted that for flow modes at which the velocity on the axis takes on negative values, this method of computation can be utilized only in the domain from nozzle cutoff to the section where $u_m = 0$.

For large Archimedes numbers, Ar_0 = 0.0094, say, when a "descending" free convective flow directed oppositely to the forced stream (see Fig. 3) is formed close to the channel walls, the computation method satisfactorily describes just the nature of the change in the velocity u_m. The computed values of the velocity u_δ do not agree with experiment which is explained by the difference between the real velocity profile in the transverse section of the channel and the computed value due to the origination of a "descending" flow near the wall. The computed velocity profile determined by (5) has the same form as for an isothermal flow. A more exact and correct description of the flow under consideration can probably be obtained for large Reynolds numbers by using numerical methods of solving the Navier—Stokes equations.

NOTATION

u, velocity component along the x axis averaged with respect to time; P, ρ, T, static pressure, density, and temperature; x, y, rectangular coordinates; T_∞, parameters taken as the reference origin of the temperature level in determination of the Archimedes force; c_p, specific heat at constant pressure; ν, kinematic viscosity; ν_T, coefficient of turbulent viscosity; g, acceleration of gravity; β, thermal coefficient of volume expansion; δ, δ_T, thicknesses of jet dynamic and thermal boundary layers; x_H, length of the jet initial section; y_0, coordinate of the zero velocity line; q, heat flux density; $\varkappa$ = 0.01, f = 1, J = 2, empirical coefficients in the turbulence model; r, d, radius and diameter; Re_T^{**}, Reynolds number computed according to the energy loss thickness; Pr, Pr_T, molecular and turbulent Prandtl numbers; $Ar_0 = g\beta(T_0 - T_{w_0})d_0/u_0^2$, Archimedes number; T_{w_0}, wall temperature in the nozzle exit section; St_0, standard heat transfer law; $\bar{u}_m = u_m/u_0$; $\bar{u}_\delta = u_\delta/u_0$; $\vartheta = T_0/T_{\delta_0}$. Substripts: 0, nozzle exit; m, δ, jet axis and boundary; w, wall, and k, channel.

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INVESTIGATION OF NONSYMMETRIC JET AERODYNAMICS

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Results are presented of experimental data on studying the characteristics of nonsymmetric jets and the influence of modal-constructive parameters on their development.

Axisymmetric and plane-parallel streams with uniform velocity field at the exit are utilized sufficiently extensively in different branches of engineering. The characteristics of such streams are sufficiently well studied at this time and there are engineering methods for their analysis [1, 2].

However, in a number of recent cases, for instance, in pneumatic automation for the development of automatic systems, in the design of gas burner apparatus with a regulatable flame and others in order to intensify the process, great interest has appeared in the production and study of nonsymmetric jet characteristics.

The development and aerodynamic characteristics of nonsymmetric jets differ significantly from the aerodynamic characteristics of axisymmetric and plane-parallel jets. There are no methodology and analysis of such jets at this time. Consequently, experiment remains the single facility for determining the characteristics of nonsymmetric jets.

Nonsymmetric jets are organized by different apparatus (circular, slot, rectangular) by installation of guiding apparatus (vanes) within or at the exit from a nozzle. They can also be obtained by the interaction of jets flowing out at definite angles. The most simple modifications of apparatus that assure organized nonsymmetric jets with different angle of deviation from the geometric axis of the unit are represented in Fig. 1.

Plane-parallel jets with a uniform velocity field are developed in the apparatus (Figs. 1a and b) with a parallel—horizontal arrangement of rotating blades at the exit and their axis agrees with the geometric axis of the apparatus. Under parallel rotation of both blades to one side, the axis of the jet being developed at the exit is shifted. As the blade position changes relative to the apparatus axis, a jet developing with a definite angle of deviation [3] can be organized at the output.

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