DEVELOPMENT OF A FREE ROUND JET AT DIFFERENT CONDITIONS AT THE NOZZLE EXIT

Yury A. Litvinenko, Henry R. Grek, Grigory V. Kozlov, Alexander M. Sorokin and Maria V. Litvinenko
Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Division of the Russian Academy of Sciences, Novosibirsk, RUSSIA

Abstract
Experimental data concerning the influence of initial conditions at the nozzle exit on the structure and development characteristics of round jets are reported. Features in the development of laminar and turbulent round jets emanating from variously elongated nozzles at identical Reynolds numbers are revealed. Smoke visualization pictures obtained for jets formed under different initial conditions (with different distributions of mean and pulsating flow velocities at the nozzle exit) are discussed. It is shown possible to make the zone of laminar flow in the jet stream more extended, and to delay the jet turbulization process in space, by making the flow-velocity profile more parabolic at the exit of elongated nozzle. Features in the development of vortical structures in a jet under an acoustic action are identified. It is shown that, for a turbulent round jet to be produced right at the nozzle exit, the nozzle length must be increased in excess of a certain value so that to provide for spatial growth of turbulent boundary layer thickness, finally ending in the formation of a fully turbulent flow velocity profile across the channel.

Keywords: round jet, smoke visualization, hot-wire measurements.

Introduction
Jet and free shear flows were the subject of many, both theoretical [1–4] and experimental [5–9], studies. Such studies are significant as they allow a better insight into the jet flow development mechanism to be gained; they are also important for various applications of such flows. For instance, jets produce thrust in rockets and airplanes, they can be used in rocket or airplane flight control, in the production of gas-liquid mixtures, and in turbines.
A jet flow is normally organized with the help of a special jet device, the so-called nozzle block, presenting, in the case of jet nozzles, a shaped head used to convert the potential energy of the moving working body (liquid, steam, or gas) into kinetic energy. As the working body moves along the jet nozzle, its velocity increases. K.G.P. Laval was the first to employ such nozzles in 1889 for raising the discharge velocity of steam flows prior to their impingement onto turbine wheels. In terms of its structure, a jet issuing from a nozzle can be laminar or turbulent, sub- or supersonic. Convergent jet nozzles are used to produce subsonic, and nozzles with a divergent head (Laval nozzle), supersonic jet flows. If the discharge velocity remains lower than the velocity at which acoustic waves propagate in the flow, then the nozzle presents just a cylindrical or convergent pipe section.

Presently, round subsonic jets are normally obtained using axisymmetric Vitoshinsky nozzles [10]. For large-scale vortical structures coming from the flow-source blades to be broken into smaller vortical structures, and for the channel flow to be homogenized prior to coming to the nozzle exit, a honeycomb and a set of cleaning grids installed in the nozzle block, in the jet device stilling chamber, are used. Here, at the nozzle exit there forms a jet flow laminar in a certain range of Reynolds numbers. The instability developing in such a jet is most often associated with the production of vortex rings, also known as Kelvin – Helmholtz vortices. The initial conditions at the nozzle exit, namely, the distributions of mean and pulsating flow velocities condition the formation of the jet structure, thus defining the instability and subsequent downstream turbulization of the jet flow. The primary instability of laminar round jets related to the production of two-dimensional Kelvin – Helmholtz ring vortices, was examined by many workers. Among recently published papers, the review [11] deserves mention, in which data concerning natural oscillations of a vortex ring, the turbulence developing in the vortex ring, and the generation of sound in ideal incompressible fluid were analyzed. S.C. Crow and F.H. Champagne [4] were the first to show that the shear layer of an axisymmetric jet contains ordered vortical structures. In

[12], measurement data were reported providing evidence that vortical structures interact with each other and can merge together. Later, a vortex-street model was proposed to predict the evolution of azimuthal vortex rings [13]. With measurements of round jet performed in the vicinity of nozzle, D. Liepmann and M. Gharib [7] showed that, initially, a primary Kelvin – Helmholtz instability develops in the flow, subsequently leading to successive rolling of shear layers into vortical structures presenting a train of vortex rings. Secondary instabilities give rise to streamwise vortical structures that interact with the primary vortex rings. The streamwise structures originate in between neighboring vortex rings; they largely affect the mixing processes and flow dynamics. V.V. Kozlov et al. [14, 15] showed that streamwise structures play an important role in the jet turbulization mechanism in which jet turbulization occurs due the interaction of streamwise structures with ring vortices. The latter interaction leads to three-dimensional distortion of these vortices and to emergence of azimuthal outbursts in the form of Λ or Ω-shaped vortices; secondary disintegration of these outbursts finally results in jet turbulization.

In the study of turbulent jets reported in [16], coherent structures were revealed. A.K. Hussain et al. [16] performed detailed measurements of coherent rings and unveiled the mechanism underlying the azimuthal vortex interaction. The experimental and numerical study of [17] showed that streamwise structures are present in between the vortex rings, these structures playing an important role in the transition to three-dimensional turbulence. J.H. Citrinity and W.K. George [18] showed that the process most important in the development of turbulent-jet coherent structures is a volcano-like “explosion” observed when an azimuthal coherent structure or a ring passes the vicinity of the potential core of the jet flow. Ring vortices inject a high-velocity fluid whose penetration into the zone between neighboring rings produces a strong shear stress that plays an important role in the downstream evolution of oppositely rotating streamwise vortical pairs. Thus, the mechanism of the development and turbulent breakdown of the round laminar jet produced by the classical subsonic nozzle (with certain initial flow conditions at the nozzle exit) is now investigated in sufficient detail. There arises a natural question: suppose that we have changed the initial conditions for the formation of the jet flow, for instance, by forming, instead of the bent profile of mean flow velocity at the exit of the classical nozzle, a parabolic profile; then, how this will affect the mechanism underlying the development of laminar and turbulent jets? Which types of instability will be now involved in the jet turbulization mechanism? What will be the structure of the laminar and turbulent jets?

In the present work an attempt is made to give definite answers to these questions. To this end, we developed a new jet setup in which initial formation conditions for round jet could be varied by changing the nozzle channel length. The structure and characteristics of the flow developing in the jet stream were examined with the help of smoke visualization and measured with a hot-wire anemometer.

3. Experimental setup and measurement procedure

A schematic representation and a photograph of the jet setup admitting variation of initial conditions (distributions of mean and pulsating flow velocities) at the nozzle exit are shown in Figs. 1 and 2. This jet setup was developed around a classical nozzle block designed as a Vitoshinsky nozzle 1 with honeycomb 2, and with a set of cleaning grids 3 installed in stilling chamber 4 (see Fig. 1). To the outlet of classical nozzle 1, extension pipes 5 of various lengths (430, 870, 1300, or 4000 mm) could be attached. The inner diameter of each pipe was equal to the outlet diameter of the classical nozzle (d = 20 mm). This configuration allowed us to vary the initial flow conditions at the nozzle exit by successively forming a parabolic profile of flow velocity in the channel and at the channel outlet unless, finally, this profile of flow velocity finally assumed, at a sufficiently large channel length, a form typical of the Hagen – Poiseuille flow through round pipe.

The air flow in the setup channel was generated by fan *6*. The velocity of the air jet flow discharged by nozzle *1*, which was measured with inclined liquid column manometer *7*, in the present experiment was U_0 = 5 m/s ($Re = U_0 \times d/v$ = 6667). Investigations of two types were carried out: smoke visualization and hot-wire measurements of the jet flow. Visualization tests were conducted by feeding the jet setup, from the fan side, with smoke produced by a commercial smoke generator *8* (see Fig. 1). The structure of the smoke-visualized jet and its evolution were registered by video camera *9* both as viewed generally and in the longitudinal and transverse cross sections of the jet illuminated with a narrow laser knife at various stations along and across the flow (see Fig. 1). A detailed description of the experimental procedure used in the present study is given in [15]; in that study this procedure was used to examine the development and turbulization mechanism of the laminar jet. Like in the present study, in [15] we examined the action of an acoustic disturbance produced by dynamic loudspeaker *10* on the jet structure. The same procedure was also used to synchronize the shedding of Kelvin – Helmholtz vortices with short IR laser pulses used to stroboscopically register and film with a video camera the interaction dynamics of ring vortices with streaky structures.

Hot-wire measurements of the jet flow were carried out using a DISA constant-resistance anemometer. The anemometer measured the time-average and pulsating longitudinal flow velocities, U and u'. Probe *11* with a 1-mm long gold-plated tungsten wire 5 μm in diameter with overheating factor 1.8 was calibrated in a free stream with the use of the modified King law: $U = k_1(E^2 - E_0^2)^{1/n} + k_2(E - E_0)^{1/2}$. Here, E and E_0 are the output anemometer voltages respectively at nonzero and zero flow velocities; and k_1, k_2 and n are constants. The power exponent n is normally close to 0.5, and the second constant, k_2, accounts for free wall convection at low flow velocities. The maximum calibration error was within 1 % of U_∞. The signal from probe *11* entered hot-wire anemometer *12* to be subsequently fed into analog-to-digital converter *13* and, then, into computer *14*, used to store the data in the computer memory, process them with a software, and represent the results in graphical form. The jet flow was probed with the hot-wire sensor across with a 0.5-mm step and along, at stations x = 2, 10, 20 mm, the distances being reckoned from the nozzle exit plane. Evolution of laminar and turbulent jets was examined. The turbulent jet was produced with the help of turbulizer *15* (see Fig. 1), presenting 5-mm wide sandpaper (mean grain size 300 μm) glued onto the inner outlet surface of the classical nozzle. With the help of the turbulizer, a laminar or turbulent flow was realized in the jet at identical flow velocities.

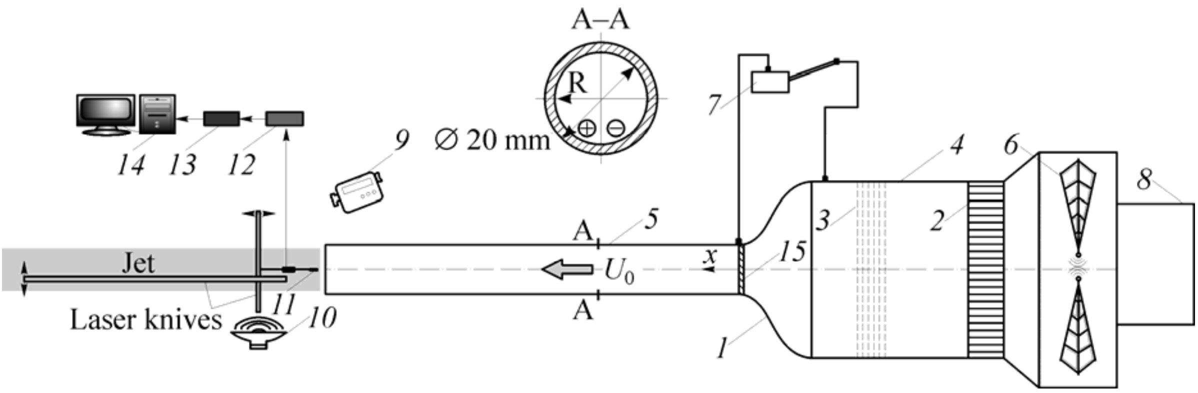


Fig. 1. The jet setup.

1 – Vitoshinsky nozzle, *2* – honeycomb, *3* – cleaning-grid set, *4* – stilling chamber, *5* – extension pipe set (430, 870, 1300, or 4000 mm), *6* – fan, *7* – inclined liquid column manometer, *8* – smoke generator, *9* – video camera, *10* – dynamic loudspeaker, *11* – hot-wire probe, *12* – hot-wire nemometer, *13* – analog-to-digital converter, *14* – computer, *15* – flow turbulizer.

The graphs were plotted across the jet flow. The abscissa axis was normalized to the channel radius as r/R, R being the radius of the cylindrical channel, and r, the current coordinate. The values plotted over the ordinate axis were normalized by the mass-mean velocity of the jet flow U_{mean} for distributions of mean flow velocity U across the jet, and by the jet flow velocity at the channel centerline U_0 for the root-mean-square pulsating velocity u' in percents of U_0. The current coordinate in the measurements performed in the downstream region of the nozzle exit is x. Other notation conventions adopted in the present paper are as follows: L/d is the extension of the channel, presenting the ratio of the channel length L to the channel inner diameter d; and l/d is the caliber extension of purely laminar jet, defined as the ratio between the length of purely laminar jet l and the inner diameter of the nozzle channel d.

4.Measurement and visualization data

The development and turbulization mechanisms of classical laminar round jet flow were previously examined in [14, 15]. The tests performed on the new setup confirmed previous results. In addition, the present facility has allowed us to examine the downstream evolution of the laminar round jet as dependent on its initial formation conditions by varying the extension of the outlet section of the nozzle, from the classical (short) nozzle to a long nozzle in which the canonical flow with Hagen – Poiseuille parabolic velocity profile was formed. All these stages are described below in more detail.

Classical round jet. Figure 2 shows the distributions of mean flow velocity U and pulsating flow velocity u' across the classical laminar round jet measured at various distances from the nozzle exit plane (see Fig. 2, a, b).

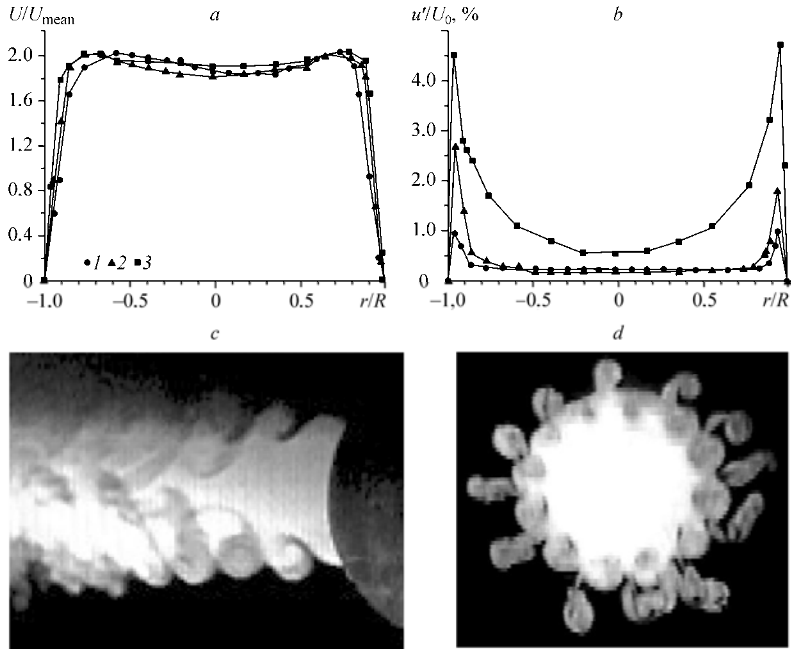
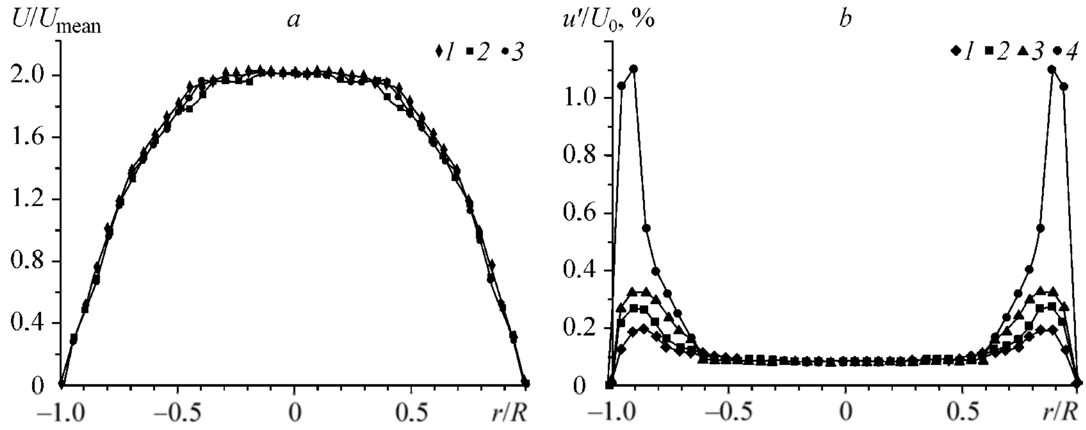


Fig. 2. Distributions of mean flow velocity (*a*) and pulsating flow velocity (*b*) across the classical round jet (curves *1*, *2*, and *3* refer, respectively, to downstream distances x = 2, 10, and 20 mm), and smoke visualization pictures taken along (*c*) and across (*d*) the jet flow. The stream velocity at the jet axis is U_0 = 5 m/s (Re = $U_0 \times d/v$ = 6667).

It is seen in the graph (see Fig. 2, a) that the distribution of flow velocity across the classical jet is Π-shaped, with slight concavity in the core region of the flow. Very probably, this shape is defined by ring vortices continuously shedding out of the nozzle in classical round jet, or with the Kelvin – Helmholtz instability. The maximum level of velocity pulsations is observed in the shear layer (see Fig. 2, b); it roughly equals 1 % U_0 near the nozzle, and then gradually increases downstream to reach a value of 4.5 % U_0. In the jet core, the pulsating velocity is much lower, increasing in the flow direction from 0.4 % U_0 to about 1 % U_0. These distributions of mean and pulsating flow velocities, typical of classical round jet, well comply with previously reported data [14, 15]. Considering the smoke visualization data, in the classical jet one can distinctly observe, in the general view, ring vortices (see Fig. 2, c) and the interaction of ring vortices with streaky structures, this interaction gives rise to cross-sectional azimuthal structures in the jet flow (see Fig. 2, d). Thus, the turbulization of the classical round jet is related to the Kelvin – Helmholtz instability originating immediately at the nozzle exit, with subsequent interaction of ring vortices with streaky structures, with the formation of azimuthal vortical structures promoting the mixing of the jet with the ambient gas medium, and also with full turbulization of the jet flow. The present study has confirmed both the well-known theoretical and experimental data concerning the development of classical round jet, previously reported by many workers, and the new experimental data obtained by the present authors in [14, 15].

4.1. Round jet issuing from the 870-mm long channel. Consider now what will happen with the jet on further channel elongation achieved by adding, to the classical nozzle, a 870-mm long pipe with inner diameter equal to the outlet diameter of the classical nozzle (Fig. 3).



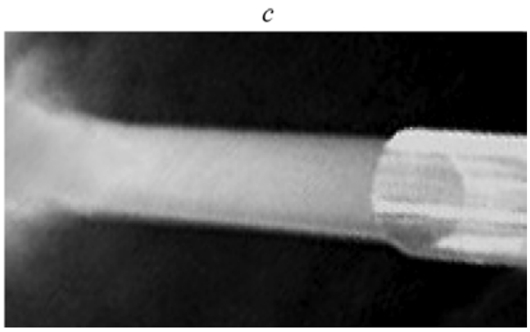


Fig. 3. Distributions of mean flow velocity (*a*) and pulsating flow velocity (*b*) across the classical round jet emanating from the 870-mm long channel at three downstream stations (curves *1*, *2*, *3*, and *4* refer, respectively, to $x = 2$, 10, 20, and 60 mm), and a smoke visualization picture taken along the flow direction (*c*). The stream velocity at the jet axis is U_0 = 5 m/s ($Re = U_0 \times d/v$ = 6667).

In the previous case we had a cross-sectional flow velocity profile with characteristically distorted parabolic shape; in the present situation (see Fig. 3, a) the profile has become more parabolic yet with a characteristic shell still retained in the jet core. The distributions of pulsating velocity u' across the jet at four downstream stations is shown in Fig. 3, b. The maximum level of velocity pulsations is observed in the shear layer; it roughly equals 0.2 % U_0 near the nozzle and increases to 1.5 % U_0 in the downstream region. In the jet core, the intensity of velocity pulsations is much lower, about 0.4 % U_0 throughout the whole measured downstream region. On the whole, in comparison with the previous cases the intensity of velocity pulsations decreases appreciably with increasing channel length although in all the cases the pulsation level increases in the flow direction. The jet itself has changed even more dramatically, which can be observed in the general visualization picture of the flow (see Fig. 3, c). It is seen that the unstructured zone with purely laminar flow became extended to four calibers ($l/d = 4$). Farther downstream, jet turbulization is observed. Thus, the further change in initial jet formation conditions has led to a more dramatic, compared to the previous case, modification of the flow pattern. Again, the laminar flow zone has become more extended, and the transition zone has displaced farther downstream.

4.2. Round jet issuing from the 4000-mm long channel. Consider now what will happen with the jet on further channel elongation achieved by adding, to the classical nozzle, a 4000-mm long pipe with inner diameter equal to the outlet diameter of the classical nozzle (Fig. 4).

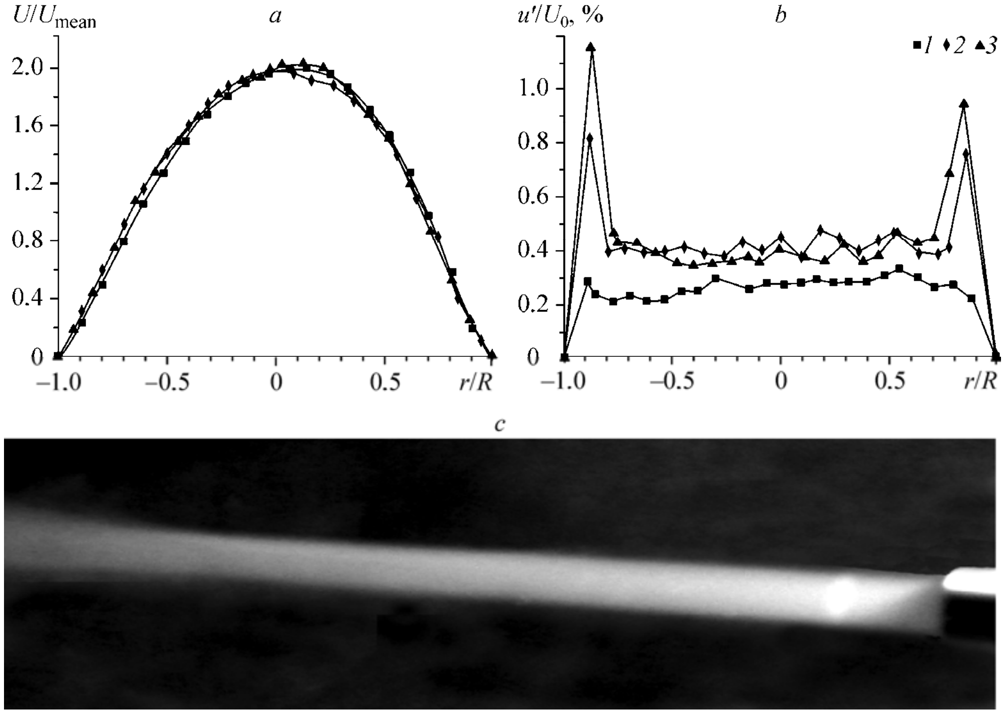


Fig. 4. Distributions of mean flow velocity (*a*) and pulsating flow velocity (*b*) across the classical round jet emanating from the 4000-mm long channel (curves *1*, *2*, and *3* refer, respectively, to downstream distances *x* = 2, 10, and 20 mm), and a smoke visualization picture taken along the jet flow (*c*). The stream velocity at the jet axis is U_0 = 5 m/s ($Re = U_0 \times d/v$ = 6667).

Previously, we had cross-sectional flow velocity profiles gradually approaching the parabolic profile. In the present situation (see Fig. 4, a) we observe a perfectly parabolic velocity profile, or the Hagen – Poiseuille profile, typical of the canonical flow through long round pipe. Cross-sectional distributions of velocity u' measured at three downstream stations are shown in Fig. 4, b. The maximum level of velocity pulsations is observed in the shear layer; it roughly equals 0.25 % U_0 near the nozzle and increases to about 1.2 % U_0 in the downstream region. In the flow core, the intensity of velocity pulsations is much lower, amounting to about 0.4 % U_0 throughout the whole downstream measurement region. On the whole, compared to the previous case, the level of velocity pulsations remained roughly unchanged, although exhibiting, as previously, the same tendency to downstream growth in the shear layer. Qualitatively, the downstream evolution of the jet flow can be traced considering the smoke visualization data (Fig. 4, c). The zone occupied by purely laminar, unstructured jet has extended to ten calibers (l/d = 10). The resolution limit of the photograph is insufficient to grasp subsequent turbulization of the jet flow in the downstream region. Thus, the change in the initial jet formation conditions defined by the length of the nozzle channel from which the jet emanated with a characteristic canonical Hagen – Poiseuille velocity profile has resulted in a dramatic change of the whole flow pattern. The laminar portion of the flow has become prevailing, whereas the transition zone has displaced far downstream.

4.Conclusions

From the present experimental study, in which the influence of initial conditions at the nozzle exit on the structure of the round jet was examined, the following conclusions can be drawn.

1. Variation of initial conditions for the formation of round jets, such as the profiles of mean and pulsating flow velocities at the nozzle exit plane, has a dramatic influence on the structure and development characteristics of the jet flow.

2. Channel elongation in the classical short nozzle changes the initial formation conditions for round laminar jets, resulting in the formation, in the jet flow, a zone with purely laminar flow whose extension increases with increasing channel elongation, reaching a value of l/d = 10 at L = 4000 mm.

3. In the case of a laminar jet, the profiles of pulsating flow velocity at the nozzle exit plane display an intensity maximum of 4.5 % U_0 in the shear layer and an intensity minimum of 1 % U_0 in the jet core. With increased channel elongation, the pulsation intensity decreases to 1 % U_0 in the shear layer and to 0.1 % U_0 in the jet core.

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