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EFFECT OF STREAMWISE STREAKY STRUCTURES ON TURBULIZATION OF A CIRCULAR JET

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Experimental investigations of the influence of streamwise streaky structures on turbulization of a circular laminar jet are described. The qualitative characteristics of jet evolution are studied by smoke visualization of the flow pattern in the jet and by filming the transverse and longitudinal sections of the jet illuminated by the laser sheet with image stroboscopy. It is shown that the streaky structures can be generated directly at the nozzle exit, and their interaction with the Kelvin–Helmholtz ring vortices leads to emergence of azimuthal "beams" (Λ-structures) by a mechanism similar to three-dimensional distortion of the two-dimensional Tollmien–Schlichting wave at the nonlinear stage of the classical transition in near-wall flows. The effect of the jet-exhaustion velocity and acoustic action on jet turbulization is considered.

Key words: *circular jet, streaky structures, visualization, Kelvin–Helmholtz vortices.*

Introduction. The knowledge of physics of mixing processes in jet flows is important for both research and applications It is known that the mixing processes are associated with the transition to turbulence [1]. These processes control the degree of gas mixing in combustion chambers, level of jet noise of airplanes and vehicles, and the spread of pollutants at industrial sites. In practical applications, it is often necessary to solve the problem of intensification of jet-flow mixing with the ambient gas. The velocity and degree of mixing affect the combustion efficiency, degree of heat and mass transfer, pollutant formation, jet-noise suppression, and reduction of size of such functional devices [1].

In addition to azimuthal vortices (or Kelvin–Helmholtz ring vortices), streamwise vortices generated in the jet flow can significantly affect the processes of mixing of fluid flows [1]. Streamwise vortices in jet flows can be generated by various methods. For instance, a lobed nozzle [2] was used to generate large-scale streamwise vortices in the jet flow; such a nozzle is a promising instrument of intensification of gas mixing in the jet. Such nozzles are widely used to control exhaust of turbofan engines and ejectors.

For instance, lobed nozzles-mixers are used in engines of Boeing and Airbus airplanes to reduce the noise of the exhaust jet and fuel consumption [3, 4]. To reduce infrared radiation signals of a military aircraft, i.e., to ensure aircraft survivability, lobed nozzles-mixers are used to enhance mixing of the high-temperature and high-velocity gas plume from the engine with the ambient cold air [5, 6]. They are mounted on Tiger helicopters (Germany and France), Comanche helicopters (USA), and F-117 stealth aircraft. Lately, lobed nozzles have been used to intensify fuel-air mixing in combustion chambers, which enhances effective combustion and reduces formation of pollutants [7].

The dynamic mechanism of mixing downstream of a lobed nozzle-mixer was first considered in [8]. It was found that such a nozzle generates streamwise vortices with a length of the order of the nozzle radius. A more detailed pattern of the jet flow exhausting from a lobed mixer is described in [9]. It was found that interaction of the Kelvin–Helmholtz vortices with the streamwise vortices produces high levels of mixing. The streamwise vortices deform the Kelvin–Helmholtz vortices into "pinch-off" structures and increase the stirring effect in the mixing flow. It follows from the studies conducted that large-scale streamwise vortices artificially generated by the lobed nozzle and azimuthal Kelvin–Helmholtz vortices play an important role in mixing of the jet core with the ambient flow.

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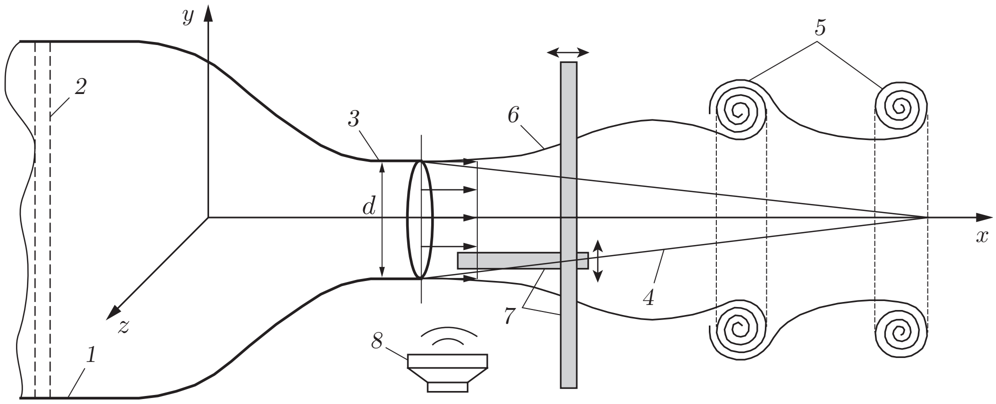

Fig. 1. Jet flow in an axisymmetric circular jet: 1) chamber; 2) deturbulizing grids; 3) nozzle; 4) potential core; 5) Kelvin–Helmholtz vortices; 6) streaky structures; 7) positions of the laser sheet; 8) loudspeaker.

In contrast to the above-described situation, where the streamwise structures were artificially generated by using a special geometry of the nozzle, Demare and Baillot [10] considered the streamwise structures generated by secondary instability of the jet itself and their role in the mixing process. It is known that the linear Kelvin–Helmholtz instability in jet flows with a certain Reynolds number downstream leads to an increase in disturbance amplitude, which rolls up the shear layer into primary axisymmetric rings [11]. Other ordered vortices due to secondary instability are also observed. These structures arise in the form of counterrotating streamwise vortices, which are superimposed onto the Kelvin–Helmholtz vortices. Such vortices were studied in plane shear layers [12, 13] and were observed in circular water jet [14]. Monkewitz et al. [15, 16] believe that formation of side jets in a hot plume is also a result of development of streamwise vortices. The presence of secondary vortices was also observed in direct numerical simulations of three-dimensional circular jets [17, 18] or shear layers [19]. The study of [13] shows that origination of streamwise vortex structures is a response of the shear layer to three-dimensional upstream disturbances. The streamwise vortex structures are first generated in the gap between two consecutive primary vortices (Kelvin–Helmholtz rings) and then penetrate into their cores. Based on the study of [10], stabilization of jet combustion can be represented as follows. Primary instability of the jet (Kelvin–Helmholtz instability) leads to emergence of the Bernal–Roshko vortex rings. Secondary instabilities of the jet generate streamwise vortices ejected in the azimuthal direction from the jet core into the ambient air, producing a typical lobed shape of the jet cross section. Counterrotating vortex pairs appear at the end faces of these lobes, which intensifies jet mixing with the ambient air. These regions of active fuel–air mixing attract the flame and stabilizes the combustion process.

Thus, the role of streamwise vortex structures in evolution of jet flows is obvious. At the same time, vortex structures in jets are strongly receptive to noise or acoustic disturbances. Hence, artificially generated disturbances can be used to considerably change and even control the development of jet structures [20] (e.g., for turbulence reduction [21, 22]). Acoustic actions can be used to change the combustion process and reduce soot formation and emission of nitrogen oxides [23] in jet burners. The experiments of [10] show that the acoustic action on the jet intensifies mixing and enhances combustion stabilization. Control of various jet flows by acoustic actions was studied in detail in [24].

The objective of the present work is to study the mechanisms of origination of streamwise vortex structures directly at the nozzle exit, their downstream evolution and interaction with the Kelvin–Helmholtz vortices, and acoustic actions on these processes in a circular jet. This work is based on the previous research [25], where it was shown that streamwise vortices are generated immediately at the nozzle exit. It seems important to study the process of origination, development, and interaction of streamwise and ring vortices.

1. Experimental Facility and Measurement Technique. The experimental facility for jet-flow generation, whose layout is shown schematically in Fig. 1, consists of a chamber with a set of deturbulizing grids, ending up by a contoured nozzle with a circular or plane output orifices (circular in the present experiment). The air flow was generated by a fan. Figure 1 also shows the classical flow pattern in an axisymmetric circular jet. The flow velocity at the nozzle exit was $U_0 = 4$ m/sec, which corresponded to the Reynolds number $\mathrm{Re}_D = U_0 D/\nu \approx 10{,}600$, the circular nozzle diameter was $D = 40$ mm, and the kinematic viscosity of air was $\nu = 1.5 \cdot 10^{-5}$ m^2/sec.

The distributions of the mean and fluctuating velocity components at different distances downstream from the nozzle exit are shown in Fig. 5 of [25].

This paper contains qualitative results obtained by smoke visualization of a circular jet flow. The flow pattern (Fig. 1) in transverse and longitudinal sections of the jet was filmed by a video camera. Triggering of the laser sheet was synchronized with the shedding frequency of ring vortices, which allowed a more detailed presentation of the jet-flow pattern at different distances from the nozzle exit both in the transverse and in the longitudinal directions. Another aspect of studying the jet-development mechanism was investigation of the acoustic action on the jet. A dynamic loudspeaker with a variable-frequency sine electric signal was used for this study. The jet experienced an acoustic action with the loudspeaker located along or across the jet. The video camera registered the flow pattern with and without the acoustic action.

2. Flow Visualization in an Axisymmetric Circular Jet. The process of development and turbulization of a circular axisymmetric jet is well known. Figure 102 of [26] shows a laminar air flow escaping from a circular tube with $\mathrm{Re} = 10\,000$ and visualized with the help of a smoke wire. Axisymmetric oscillations (Kelvin–Helmholtz instability) are developed in the external region of the jet, and then this part of the jet rolls up into vortex rings (Kelvin–Helmholtz vortices), after which the jet suddenly becomes turbulent. The structure of the smoke ring is shown in Fig. 77 of [26]; it is a tightly wound toroidal spiral arising because of roll-up of the vortex sheet shed from the nozzle edges. The transition of the laminar jet to a turbulent state is caused first by primary instability (Kelvin–Helmholtz instability) and then by secondary instability of vortex rings. Figure 118 of [26] clearly displays vortex-ring instability caused by increasing waves around the vortex ring, which is often called the Widnell instability. As was noted in Introduction, the mechanism of origination and development of these waves is usually explained by interaction of the Kelvin–Helmholtz vortices and streamwise vortices. The process of generation of streamwise vortices in the jet flow, however, is not yet clear. These vortices can be artificially generated by a specially contoured nozzle or they can arise as a result of secondary instability of the jet itself. It was shown [25] that streamwise streaky structures are generated directly at the nozzle exit as a result of boundary-layer lift-up ("lift-up" effect). It was also found that secondary high-frequency disturbances facilitating rapid turbulization of the jet can develop on these vortices. The mechanism of interaction of ring vortices with these streamwise structures has not been adequately studied. At the same time, the mechanism of interaction of streamwise vortices generated by secondary instability of the jet with ring vortices was studied in detail in [10]. It was shown in [10] that counterrotating streamwise vortices are ejected in the azimuthal direction between the neighboring ring vortices, which intensifies jet mixing with the ambient air over the entire jet periphery. Demare and Baillot [10] attributed generation of streamwise vortices to secondary instability of the jet itself, which is accompanied by a train of ring vortices.

3. Results of an Experiment without Controlled Disturbances. The results of smoke visualization of a circular jet under natural conditions are shown in Fig. 2. Figure 2a reveals two ring vortices in the laminar flow region, jet expansion in the downstream direction, and turbulent flow region. Figure 2b shows azimuthal "beams" uniformly distributed over the circular jet periphery.

As was shown in [25], the presence of beams indicates the existence of streaky structures generated directly at the nozzle exit. The region ahead of the ring vortex ($x = 13$ mm) and the region of the ring vortex ($x = 20$ mm) are shown in Fig. 2b and c, respectively. In the latter case, the intensity and size of the beams are greater, which is caused by interaction of the ring vortex with streaky structures, since the two-dimensional ring vortex experiences three-dimensional distortion on flow inhomogeneities caused by the presence of streamwise streaky structures. The mechanism of this distortion is similar to three-dimensional distortion of the two-dimensional Tollmien–Schlichting wave at the nonlinear stage of its development, when typical three-dimensional Λ-structures appear. In the classical experiment [27], the Λ-structures were obtained owing to three-dimensional distortion of the Tollmien–Schlichting wave on local inhomogeneities of the flow; in our case, streamwise streaky structures act as local inhomogeneities. The two-dimensional vortex ring passes through the region of evolution of streamwise structures, interacts with them, and experiences three-dimensional distortion, which results in typical azimuthal "lobes" resembling the Λ-structures. An acoustic action on the jet intensifies jet interaction with streaky structures. Figure 3a and b shows the jet cross section $x/d = 0.5$ without and with the acoustic action, respectively. In the latter case, interaction of the ring vortex and streaky structures is stronger: the beams increase in size and acquire a mushroomlike shape. The mushroomlike shape of the beams in the case of interaction of streamwise and ring vortices was also noted in [10].

Thus, flow visualization in a circular jet under natural conditions supports the existence of ring vortices and streaky structures generated directly at the nozzle exit. The acoustic action amplifies interaction between streaky structures and ring vortices. It should be noted that streaky structures are subjected to the action of radial

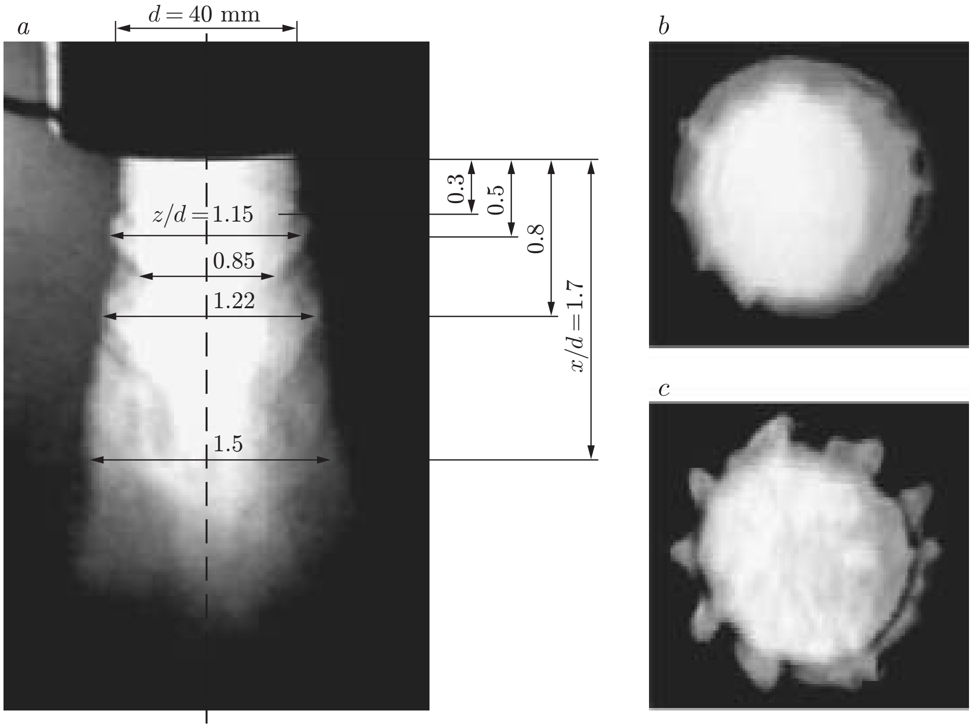

Fig. 2. Results of smoke visualization of a circular jet: overall view (a) and jet cross sections $x/d = 0.3$ (b) and 0.5 (c).

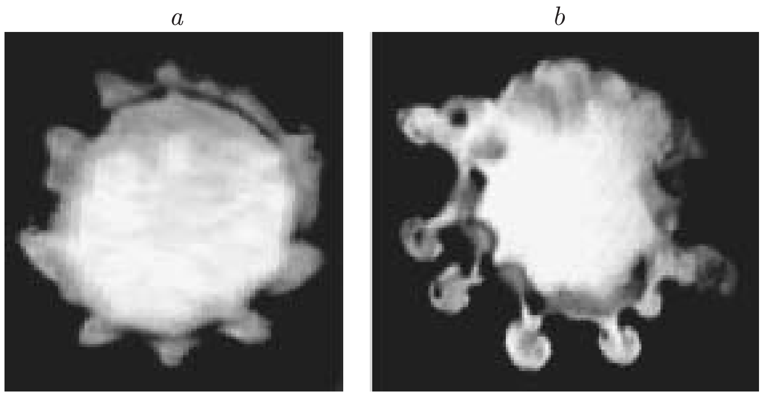

Fig. 3. Smoke visualization of the jet cross section $x/d = 0.5$ without (a) and with (b) the acoustic action.

oscillations, which makes observation and measurement of the flow structure more difficult. Therefore, natural streaky structures were reproduced artificially by 12 roughness elements 0.2 mm high and 5 mm wide, which were glued onto the inner surface of the nozzle (near the exit). The roughness size correlated with the scale of natural streaky structures.

4. Results of an Experiment with Controlled Disturbances. Let us consider the jet flow in the transverse and longitudinal directions with introduction of controlled disturbances in more detail. The results of visualization of this flow at different distances downstream from the nozzle exit are shown in Fig. 4. Near the nozzle (Fig. 4b), the external boundary of the ring vortex has a sinusoidal shape over the entire circumference. At $x/d = 0.3$ (Fig. 4c), the sinusoidal contour is distorted, and azimuthal beams appear, which is caused by interaction of the first ring vortex and streamwise structures generated at the nozzle exit. Further downstream ($x/d = 0.5$, Fig. 4d), distortion at the center of the first ring vortex increases, and the azimuthal lobes (beams) acquire the shape of narrow pins with mushroomlike structures at the ends; these mushroomlike structures are similar to those observed in [10] and identified as a pair of counterrotating vortices. In the region between the first and second ring

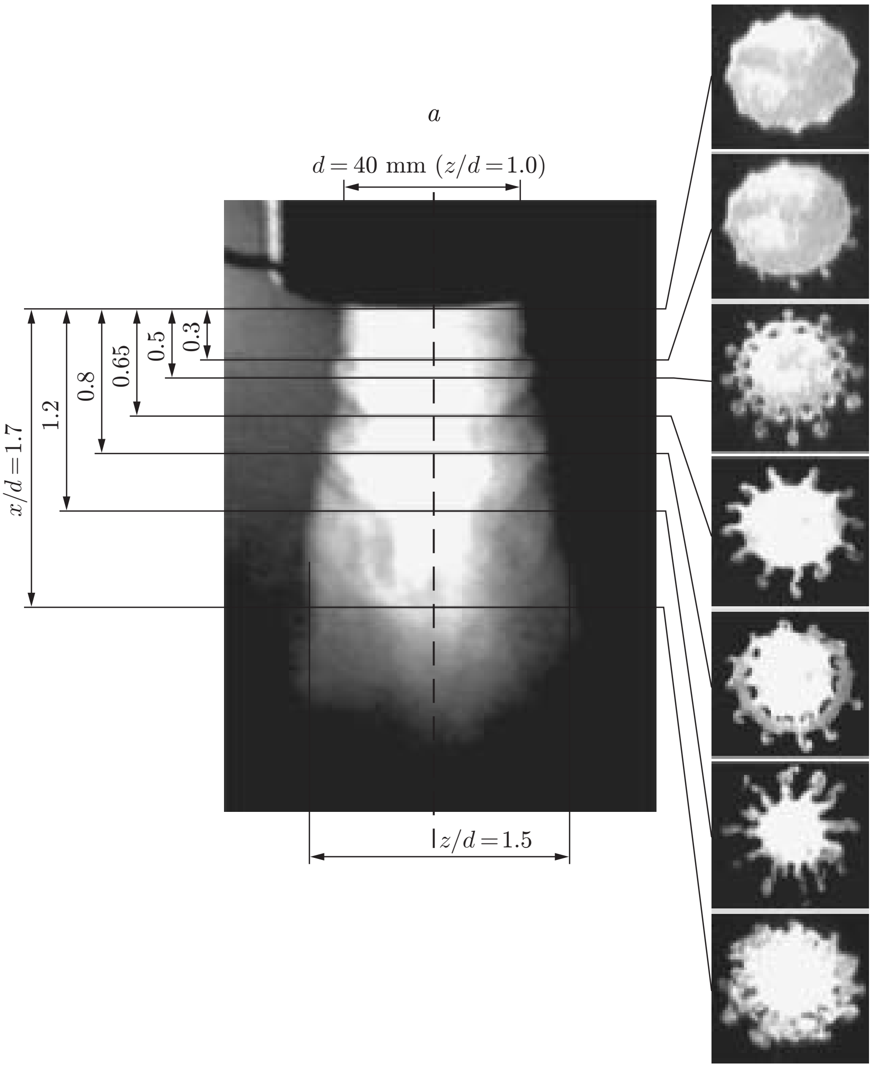

Fig. 4. Smoke visualization of a circular jet (a) and its cross section at different distances from the nozzle exit (b–h).

vortices ($x/d = 0.65$, Fig. 4e), the ring structures are not observed, but the beam intensity increases. At $x/d = 0.8$ (Fig. 4f), there appears the second ring vortex, and the beams are intensely developed, especially after passage of the second ring vortex at $x/d = 1.2$ (Fig. 4g). Further downstream, intense mixing of the jet with the ambient gas is observed due to development of the beam structures until the entire jet becomes turbulent at $x/d = 1.7$ (Fig. 4h). Stroboscopy allows one to observed interaction of ring vortices and streaky structures further downstream.

Thus, the process observed is caused by interaction of streaky structures and ring vortices in the downstream direction. Three-dimensional distortion of the two-dimensional Tollmien–Schlichting wave at the nonlinear stage of its evolution leads to origination of the so-called Λ-structures. In the classical experiment [27], the Λ-structures are artificially generated by local inhomogeneities, i.e., three-dimensional distortion of the two-dimensional wave is prescribed beforehand. Structures similar to Λ-structures are also observed in our case, but we have a two-dimensional vortex ring instead of a two-dimensional wave and streaky structures instead of roughness elements. Three-dimensional distortion of the two-dimensional ring on local inhomogeneities of the flow (streaky structures) leads to origination of Λ-structures over the entire perimeter of the ring vortex in the azimuthal direction. It is commonly known that the Λ-structure consists of two counterrotating vortices ending by a head. The mushroomlike lobes in the azimuthal direction from the ring vortices, which are observed on visualization patterns, are, apparently, the heads of the Λ-structures. At the same time, in contrast to the boundary layer, where the Λ-structures start to develop from the wall where flow velocity equals zero toward the upper edge of the boundary layer where the

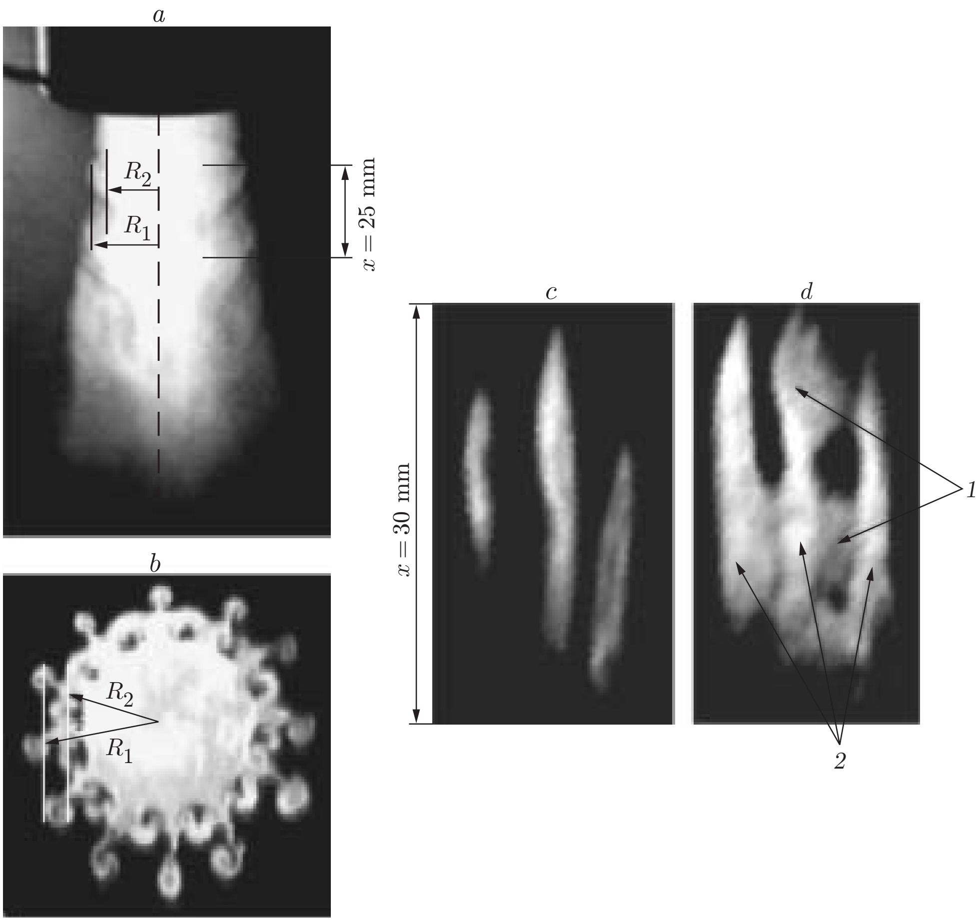

Fig. 5. Smoke visualization of a circular jet in the streamwise direction in the region of the heads of azimuthal vortex structures and their legs: general view of the jet (a); cross-sectional view of the jet (b), and longitudinal sections of the jet at R_1 and R_2 (c and d, respectively); the positions of the ring vortices and streaky structures are indicated by 1 and 2, respectively.

velocity acquires the free-stream value, entrainment of two counterrotating vortices ("legs" of the Λ-structure) in the azimuthal direction from the vortex ring occurs from the region with a high velocity toward the region with zero velocity of the gas surrounding the jet. For this reason, the head of the Λ-structure is located in the region with zero velocity, and the legs are located in the region of the maximum velocity of jet exhaustion; hence, the head lags behind the legs and the structure is extended in the downstream direction. This is evidenced by the typical yokelike shape of the ring vortex in Fig. 4a. Since visualization of the jet cross sections with different coordinates in the downstream direction (Fig. 4b–h) reveals passage of the first (Fig. 4d) and second (Fig. 4f) ring vortices, apparently, only the external part of the spiral of the ring vortex is subjected to three-dimensional distortion due to interaction with streaky structures, leading to formation of beams (Λ-structures).

The results of smoke visualization of the circular jet in the region of azimuthal beams in the longitudinal (x) direction are shown in Fig. 5. The photographs are taken in the region of the heads of the Λ-structures (in the region of the radius R_1) and in the region of their origination from the ring vortex (in the region of the radius R_2). In the region of the heads, there are three smoke stripes whose length is greater than the distance between two neighboring ring vortices (Fig. 5c). This is clearly seen in Fig. 5d (because the photograph is taken in the region of the ring vortices): the vertical stripes of smoke visualizing the streamwise structures of azimuthal lobes pierce the distance between the neighboring ring vortices and go beyond them. This fact indicates that the streamwise streaky structures are probably present along the entire jet until its turbulization.

Dependence of Jet-Evolution Dynamics on Velocity of Gas Exhaustion. Figure 6 shows the results of smoke visualization of the jet cross section for different jet velocities. The above-described process of downstream turbulization of the jet can also be observed with increasing flow velocity from a viewpoint at a fixed distance downstream

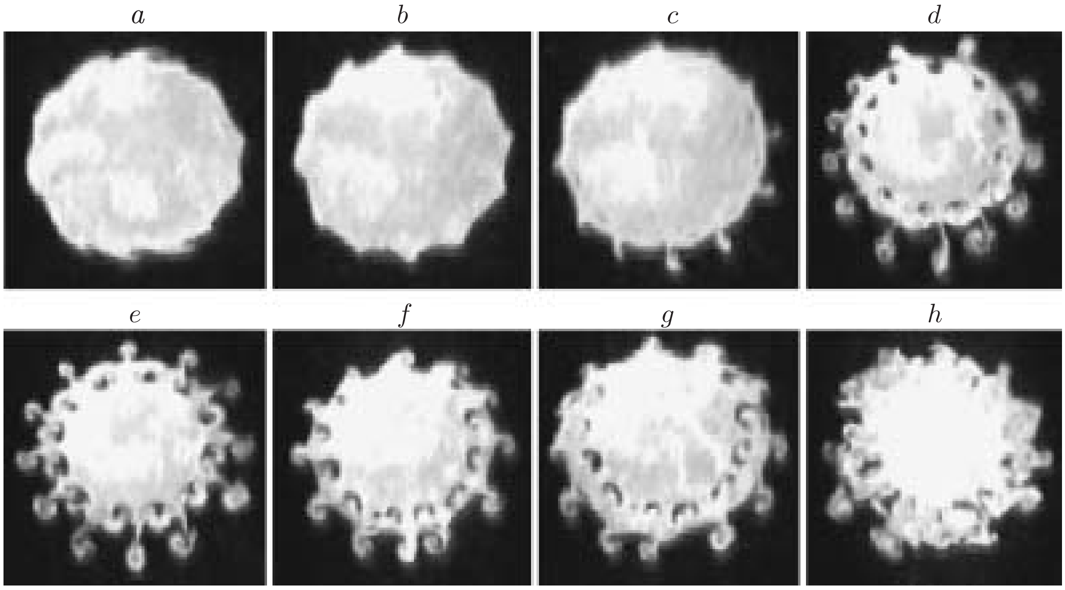

Fig. 6. Smoke visualization of the cross section of a circular jet for different jet velocities: $U_0 = 6$ (a), 7 (b), 8 (c), 9 (d), 10 (e), 11 (f), 12 (g), and 13 m/sec (h) ($x/d = 0.3$).

from the nozzle. The visualization pictures show the stages of development (Fig. 6a and b) and interaction of streaky structures with ring vortices (Fig. 6c–g), evolution dynamics of azimuthal Λ-structures (Fig. 6c–g), and turbulization of the jet (Fig. 6h).

The following criteria can be used to distinguish the laminar and turbulent flows in the jet:

1) results of hot-wire measurements of velocity fluctuations at different downstream distances (see [25, Fig. 5]) show that the level of fluctuations in the jet drastically increases at $x = 32$ mm (approximately fourfold as compared to the level of fluctuations in the laminar region at $x = 8$, 12, and 22 mm), which indicates jet-flow transition to a turbulent state;

2) visualization pictures (see Figs. 4h and 6h) reveal a random structure typical of a turbulent flow, whereas an ordered flow structure with deterministic elements is observed upstream (see Fig. 4b–g) and for a lower velocity of the flow (see Fig. 6a–g), which is typical of laminar and transitional flows.

Jet Evolution under an Acoustic Action. As was noted above (see Sec. 3), a harmonic acoustic action with an amplitude of 90 dB and a frequency of 140 Hz on the jet intensified the development of streaky structures and their interaction with ring vortices near the nozzle. Further downstream, jet turbulization under the acoustic action was accelerated in space, and an increase in the amplitude of azimuthal lobes was observed, which suggests that the acoustic action activates mixing. It is known that the amplitude of toroidal vortices increases [24], but the influence of the acoustic action on origination of streaky structures generated directly at the nozzle exit, their development, and interaction with ring vortices have not been adequately studied. It is planned to quantitatively examine the parametric characteristics of the acoustic action and the possibility of controlling the evolution of both streamwise structures and ring vortices, as well as their interaction, by acoustic actions.

Thus, the results of visualization of the circular jet show that its turbulization is caused by the process of three-dimensional distortion of ring vortices on flow inhomogeneities due to streaky structures (streamwise vortices), which leads to formation of Λ-structures, their evolution, and breakdown by the type of breakdown of a laminar boundary layer, resulting from evolution of the two-dimensional Tollmien–Schlichting wave. The scenarios of three-dimensional evolution of two-dimensional disturbances such as a ring vortex and an instability wave are shown in Fig. 7.

The apparent reasons for emergence of streaky structures directly at the nozzle exit are the deturbulizing grids in the plenum chamber of the jet unit, generation of the Görtler vortices on the concave surface of the confuser, and finally, generation of streaky structures in the boundary layer of the nozzle due to the lift-up effect. All these assumptions require detailed investigations. One such investigation was performed by Zharkova et al. [28] who found streamwise vortices in the boundary layer on a wing at high angles of attack. These vortices were generated by a grid located in the free stream.

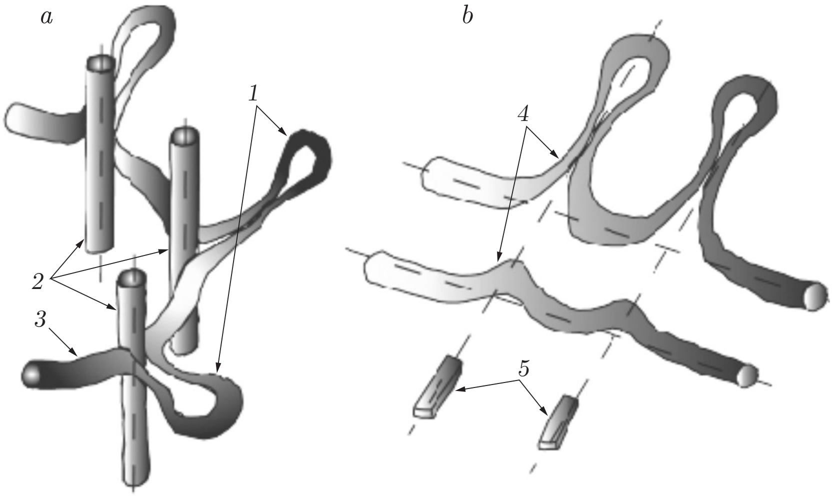

Fig. 7. Scenarios of three-dimensional evolution of two-dimensional disturbances due to interaction of the ring vortex with streaky structures (a) and three-dimensional deformation of the Tollmien–Schlichting wave (b): 1) Λ-vortices; 2) streaky structures; 3) ring vortex; 4) three-dimensional distortion of the two-dimensional wave; 5) roughness elements.

Thus, detailed visualization of the flow with the use of a synchronized laser sheet showed that streamwise vortex structures in a circular laminar jet can be generated directly at the nozzle exit. It was also found that the mechanism of interaction between ring vortices and streaky structures is a classical scenario of three-dimensional distortion of a two-dimensional wave (ring vortex) on flow inhomogeneities (streaky structures) developed in the shear layer of the jet. This process leads to emergence of azimuthal beams, which are elements similar to Λ-structures uniformly distributed over the entire perimeter of the ring vortex. The jet is intensely mixed with the ambient gas in the region of the heads of the Λ-vortices, which leads to additional azimuthal expansion of the jet.

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