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LONGITUDINAL STRUCTURES IN THE NEAR FIELD OF A PLANE WALL JET

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In the present study, the flow field near the orifice of a plane wall jet is in focus. Two main flow regions may be distinguished in the wall jet, i. e., a free shear layer away from the wall and a boundary layer close to the surface. In both of these layers, streamwise coherent structures are detected by means of smoke visualization and hot-wire measurements. The structures, which occur naturally, have different spanwise scales and emerge at different distance from the nozzle. Effects of the flow velocity, upstream perturbations, and acoustic excitation on the generation and characteristics of the streamwise disturbances are investigated, and especially the interaction between the two layers is studied. In order to resolve the complex 3D flow by means of hot-wires a system for accurate automated traversing and data acquisition has been developed. In each flow case time-dependent measurements were taken in (X, Y, Z) space of about 3000 to 25,000 points, and it was found that the value of outlet velocity and the frequency of Kelvin — Helmholtz rolls have a clear influence on the size of the structures. Higher outlet velocities and higher frequencies of triggered two-dimensional roll-ups lead to a decrease in the size of longitudinal structures.

INTRODUCTION

A turbulent wall jet may generally be considered as a flow field produced by the injection of a high-velocity fluid in a thin layer close to a surface. Such flows are of large interest in many engineering applications like film cooling of gas turbine blades, combustion chambers, and defrosters for cars or boundary layer control of aerofoils and flaps. In principle, a wall jets may be considered as a two-layer flow with an inner layer up to the point of maximum velocity most similar to a wall boundary layer, and an outer layer with a flow pattern closely related to a free shear layer. The inner and outer regions of the wall jet strongly interact forming a complex flow.

By investigating the flow field close to the outlet of a plane wall jet (the near field) the development of flow structures can be thoroughly examined since in this region the mean velocity profile is well defined, and the influence from the secondary flow is negligible. In the outer layer of the wall jet, the free shear layer, the mean velocity profiles reveal a clear point of inflection, and hence, are subject to inviscid instabilities. In a free shear layer, the two-dimensional rollers of Kelvin — Helmholtz instability determine mainly mixing process. The development of 2D motion as it has been pointed out, e. g., in [1], is often coupled with secondary streamwise coherent structures, which originate from an internal instability of the primary vortices. It was found experimentally, e. g., in [2, 3] that location of transition to three-dimensionality is dependent on the location of the origin and the magnitude of upstream perturbations. In addition, it was found that the streamwise vortices are formed in the braids between 2D rolls and then they penetrate into cores. The same result was obtained by the authors of [4], who pointed out the importance of the streamwise vorticity in the mixing process and formation of internal flow structure in the near field of circular jet. The experimental investigations of the free shear flow are supported by many numerical studies, among these the authors of [5–7], found that the three-dimensional instability exists in free shear flows. At high amplitudes, the instabilities manifest themselves mainly as counter-rotating streamwise vortices which are formed on the braids between the spanwise coherent two-dimensional pairing modes.

Noteworthy is that in free shear flows the three-dimensional small scales are observed but they may not necessarily destroy the above-mentioned large-scale two-dimensional structures. On the other hand, numerous studies of wall-bounded shear flows show the opposite that the three-dimensional effects have the most central role in the breakdown to turbulence. Based on these findings, the wall jet constitutes an excellent flow case for studying how a mixture of a free shear and a wall-bounded flow interacts through a detailed investigation of the interplay between two- and three-dimensional structures in the flow breakdown to turbulence.

To this end, very few experiments on the 3D laminar-to-turbulence breakdown process have been reported on wall jets, experimental studies cover cases of wall-jet flow over concave and convex walls. Both these curved-wall flows have been shown to be unstable with respect to a streamwise motion. Mattson [8] studied curved wall jet on the concave wall, and Likhachev et al. [9] made flow visualization together with correlation measurements which revealed the existence of large streamwise vortices in a turbulent wall jet attached to a circular cylinder. It is believed that on a curved surface the vortices are associated with the centrifugal instability.

In the present experiments, all effects of curvature are excluded, and the streamwise vortices in the wall-jet flow over a plane surface are studied purely from the viewpoint of interaction between two- and three-dimensional structures. Effects of the flow velocity, upstream perturbations, and acoustic excitation on the generation and characteristics of the streamwise disturbances are investigated. This is done by smoke-visualization and a "hot-wire visualization" method that is relying on numerically measured instantaneous velocities.

EXPERIMENTAL SETUP

All experiments were conducted at the Chalmers University of Technology and in the wall-jet facility as shown in Fig. 1. The wall jet is formed by an injection of air out of a slot, height (b) 11 mm, width 500 mm, and is developing over a large horizontal flat plate (length 2.1 and width 3.2 m) which is made of wood and coated with a thin plastic laminate. A coordinate system is defined in Fig. 1 with X in the streamwise-, Y in the

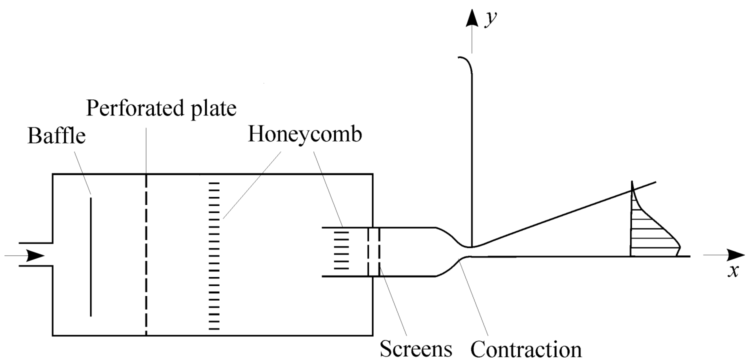

Fig. 1. Wall jet facility.

normal- and Z in the spanwise-direction. A vertical backwall (height 1.2 m) is placed over the inlet in order to give well-defined boundary conditions and to avoid disturbances around the inlet.

The experimental investigations were conducted by means of smoke visualization and "hot-wire visualization", and instantaneous velocity was measured. Air is supplied by a frequency controlled centrifugal fan to the settling chamber, which is equipped with flow straightening devices (baffle, perforated plate, honeycomb, and screens). After the settling chamber the flow enters a smooth contraction (area ratio 36:1). The turbulence level, measured at an exit from nozzle in frequency band from 10 Hz up to 10 kHz, was less than 0.05 %. During the measurements, the velocity in the middle of the inlet, U_0, was controlled by the pressure drop over the contraction, which was calibrated versus a Prandtl tube.

The streamwise velocity component was measured with a constant temperature anemometer using tungsten single wire probes with a wire diameter and length of 5 μm and 1 mm, respectively. Calibration of the hot-wire was carried out against the Pitot tube measurements at the jet exit. The manometer used (FSO510) is equipped with sensors for temperature and absolute pressure readings. The calibration curve used was

$$U = k_1(E^2 - E_0^2)^{1/n} + k_2(E - E_0)^{1/2},$$

where E is the anemometer voltage at the velocity U, E_0 the voltage at zero velocity, and the coefficients k_1, k_2, and n are determined from the best fit of the data to the calibration function. Typically the calibration procedure resulted in an error less than 0.5 % for all points in the studied velocities range.

For measurements in a jet the traverse system was used. The system is computer controlled and can be completely automated for long experimental runs through the definition of a geometrical mesh of measurement points. Traverse is free to move in 3 planes. Equipped with servo-motors it can sustain an absolute coordinate system with accuracy of 10 μm in X and Z, 5 μm in Y, and 0.01° in angular directions.

The 2D waves in plane wall jet were generated by loudspeaker which was installed in 2 meters from nozzle. The digital generator was used for generation of sinusoidal disturbances with controllable frequency and amplitude. In the visualization study, the jet was seeded with smoke particles produced by a smoke generator. The smoke was distributed into pressure chamber via the blower. A light sheet was used to visualize the flow, and the wall jet crossed the light sheet in two directions: perpendicularly and parallel to flow.

NEAR FIELD OF THE WALL JET UNDER NATURAL CONDITIONS

The flow-visualization gave unique information on the streamwise structures location and their characteristic scales. In Fig. 2, a visualization of the instantaneous flow pattern (1–2 μs) at Reynolds number of $0.5 \cdot 10^4$ is shown. The light sheet is parallel to the wall (Fig. 2, *a*), and the streamwise streaks are clearly visible in the plane formed by the X and Z coordinates, XZ cross section. Right part of this figure shows the YZ cross section under the same conditions. Here, patterns of well-defined streamwise structures are obvious. The Kelvin — Helmholtz instability arises first, which leads to sequential roll-up of shear layer into vortex structures. Similar observations have been made in the circular jet [10], where streamwise structures were shown to exist, and these evolved and amplified in the braid region between primary vortical structures. In Fig. 2, *b* the light sheet is a normal surface to the wall. The streaks occur in almost fixed spanwise positions, so this suggests that they might be associated with some disturbances originating upstream in the settling chamber.

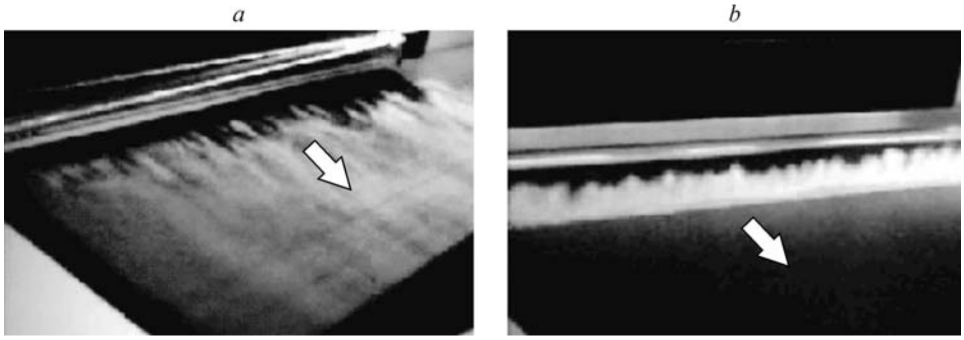

Fig. 2. Smoke visualization of the wall-jet flow under natural conditions in *XZ*-plane (*a*) and *YZ*-plane (*b*).

Jet nozzle is located at the background.

Two main flow regions are distinguished in the wall jet, that is, a free shear layer removed from the wall and a boundary layer close to the surface (Fig. 3). In the near wall region measurements show that flow is initially laminar and is well approximated by Blasius velocity profile. Further downstream, approximately from $X/b = 5$, high turbulence intensity of the upper part of the wall jet leads to transition in the inner region and, hence, breakdown of similarity. In the outer part of the wall jet (Fig. 4, *a*) in the streamwise range $0.5 < X/b < 2.5$, shear layer profiles are similar when scaled with the local maximum velocity and momentum thickness.

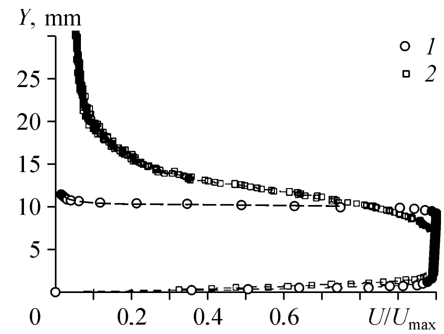

Fig. 3. Mean velocity profiles at $U_i = 8$ m/s, $X = 1$ (*1*), 51 (*2*) mm.

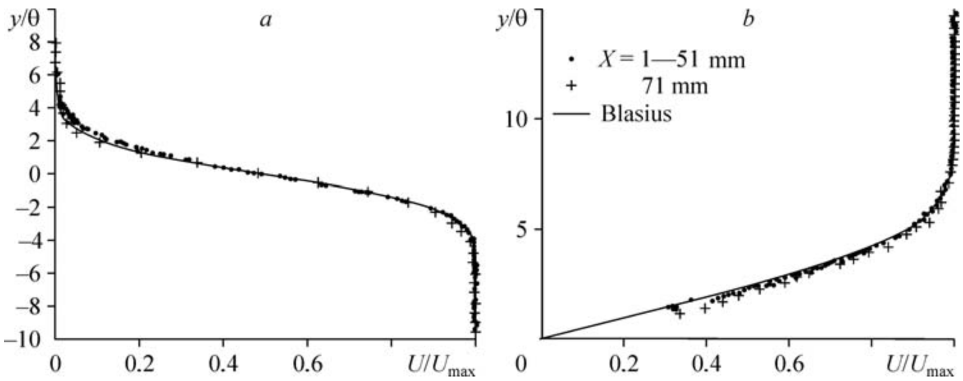

Fig. 4. Mean velocity profiles in the near field of the wall jet. In the near-wall region, profiles are initially close to Blasius (*a*) and the top part of the wall jet reveals typical shear layer profiles (*b*).

In order to stabilize the three-dimensional flow pattern, roughness elements were positioned at the orifice of the wall jet, and in this case, forced streaky structures appear not in random but in predicted positions, and this allows detailed hot-wire investigation of the flow. The array of 5 roughness elements used was positioned onto the inner surface of the top lip of the nozzle (at the exit), and each of them had a thickness of 0.22 mm, a length of 15 mm and a width of 7.5 mm. The mean velocity profiles for different positions behind roughness elements and for different x coordinate to evidence about the velocity behind roughness element is lower than between roughness elements. Starting with 20 mm in downstream direction, the maximum of RMS is located at the top of shear layer.

For better presentation of evolution process of the disturbances, the area of measurements included undisturbed regions of flow. In data-handling procedure, the undisturbed profiles were subtracted from common data. Thus, the defect of mean velocity is obtained. Then the isosurface was plotted for equal values of velocity for different cross sections.

The hot-wire results obtained with the roughness elements are shown in Figs. 5 and 6 where the free shear layer and the boundary layer of the wall jet are shown. The streamwise structures, which occur naturally in these layers, have different spanwise scales emerging at different distances from the nozzle. It was found that streaks artificially triggered in the free shear layer also stabilize the disturbance pattern in the boundary layer, but in this case eigen spanwise scale in boundary layer is different, and Fig. 6 shows naturally occurring pattern in the wall shear layer. Measurements in the upper region of the wall jet were made with the resolution of 5 mm in X, 0.5 mm in Y, and 2 mm in Z directions, and in the near-wall region, the resolution in Y direction was 2 times higher (0.25 mm). These two figures show isosurfaces of the mean velocity defect/excess relative to the mean velocity averaged in spanwise direction. It should be noted that Y-axis in Fig. 6 is three times stretched compared to Fig. 5. It can be seen that the structures of the wall boundary layer are quite different from the outer structures, and the characteristic spanwise scale near the wall is about twice as large as in free shear layer. Fully in

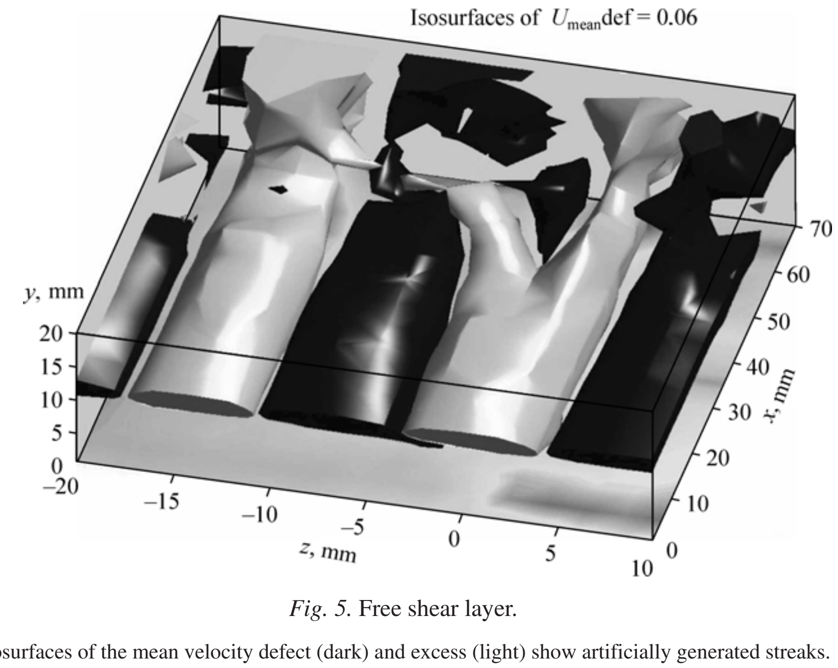

Fig. 5. Free shear layer.

Isosurfaces of the mean velocity defect (dark) and excess (light) show artificially generated streaks.

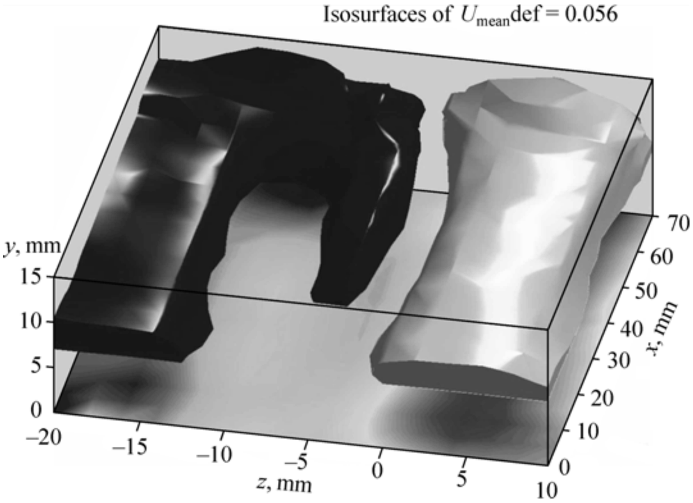

Fig. 6. Boundary layer.
Isosurfaces of the mean velocity defect (dark) and excess (light).

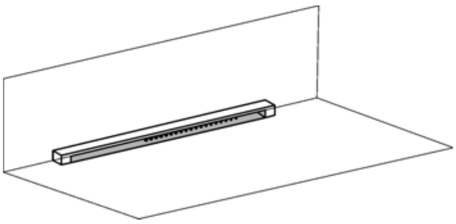

Fig. 7. Location scheme of the roughness elements inside the nozzle.

agreement with the classical transition process, the activity of the three-dimensional structures in the inner region plays a more crucial role in the transition than in the outer flow where the two-dimensional rollers are dominating.

The important questions arising here are: what is the preferred scale of longitudinal structures, and how the size of the roughness elements used affects the generation of streaks. The next experiment with roughness elements was conducted, where the roughness elements with the width of 5, 7.5, 10, and 12.5 mm were used. Four roughness elements of each size were positioned onto the inner surface of the nozzle and to create desired periodicity the spacing within a group of humps of identical size was equivalent to their size, e. g., roughness elements of 5 mm width were distributed with 5 mm spacing and so on (Fig. 7).

Figure 8, *a* shows resulting distribution in the flow field in the top shear layer, where the visualization was made using the same hot-wire technology and traverse system as was described previously. In the figure, the 5 mm roughness elements are positioned on the left with a continuing increase in their size towards right, and experimental data were taken at 24,336 points with the same spatial resolution as in Fig. 4. It can be seen that at initial stage, the most amplified vortical structures develop behind large roughness elements of 10 and 12.5 mm size, so the calculated spanwise wavelength of preferred scales is about 20–25 mm.

The influence of the Reynolds number on the characteristics of the streamwise structures was also checked, and visualizations similar to that in Fig. 8, *b* were obtained at other exit velocities, U_i. It was found that velocity increase leads to the acceleration of transition to turbulence and decrease of characteristic scale of longitudinal structures. This fact can be explained by the changes of the scale of shear layer: as the velocity of the jet increases it leads to a thinner shear layer, and hence, the size of the longitudinal structures decreases as the Reynolds number increases. These results are summarized in Fig. 9.

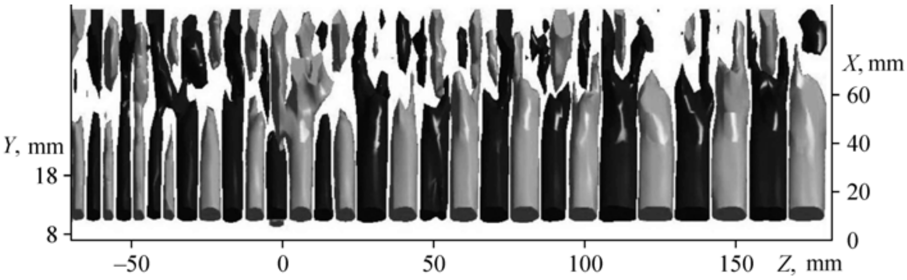

Fig. 8. Streamwise streaks created in the free shear layer by the roughness elements with varying periodicity.

Isosurfaces of the mean velocity defect (light) and excess (dark). Flow direction is from bottom to top. U_i = 8 (*a*), 15 (*b*) m/s.

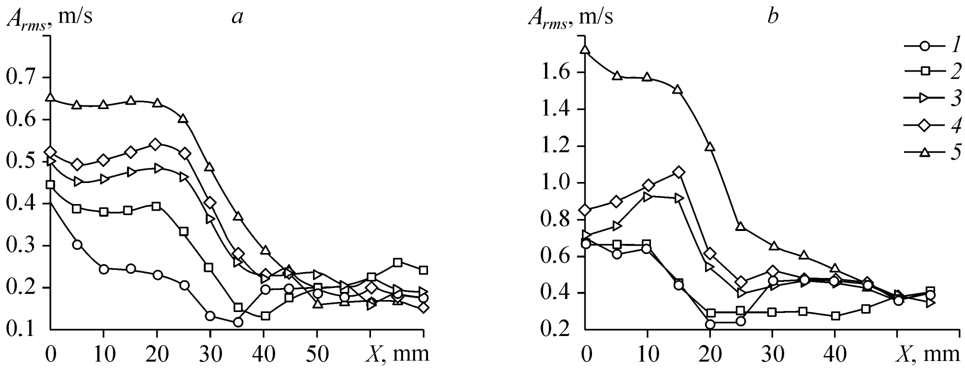

Fig. 9. Growth of different streak scales at 8 m/s (*a*) and at 15 m/s (*b*).

Streak wavelength: 5 (*1*), 10 (*2*), 15 (*3*), 20 (*4*), 25 (*5*) mm.

STREAKS INFLUENCED BY ACOUSTIC FORCING

The artificial forcing of the Kelvin — Helmholtz instability in the free shear layer of the wall jet allowed us to study the frequency effect of 2D rolls on the generation and characteristics of the streamwise disturbances. By means of a loudspeaker positioned in close surroundings of the jet outlet the instability waves of various frequencies were generated, and it was found that the frequencies of Kelvin — Helmholtz rolls have a clear influence on the size in transverse direction and amplitude of the streamwise vortical

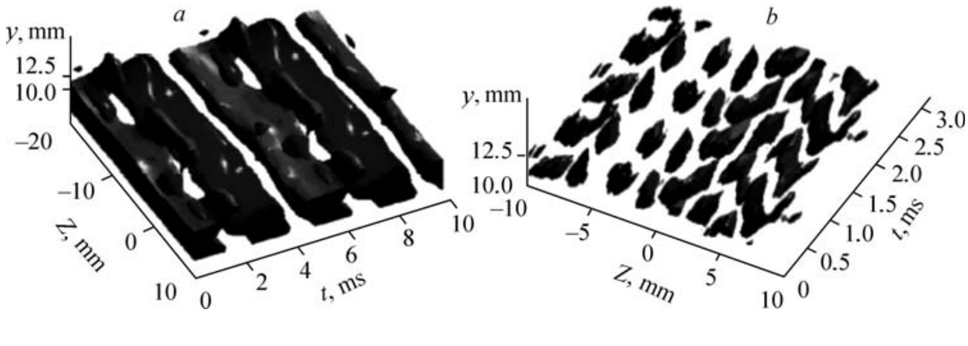

Fig. 10. Isosurface of streamwise velocity distortion due to streak and acoustic forcing.

The acoustic frequency is 200 Hz (*a*) and 700 Hz (*b*). Jet outlet velocity is 8 m/s.

The isosurface level: U_{max} = 0.3 (*a*), 0.4 (*b*), x = 41 (*a*), 21 (*b*) mm.

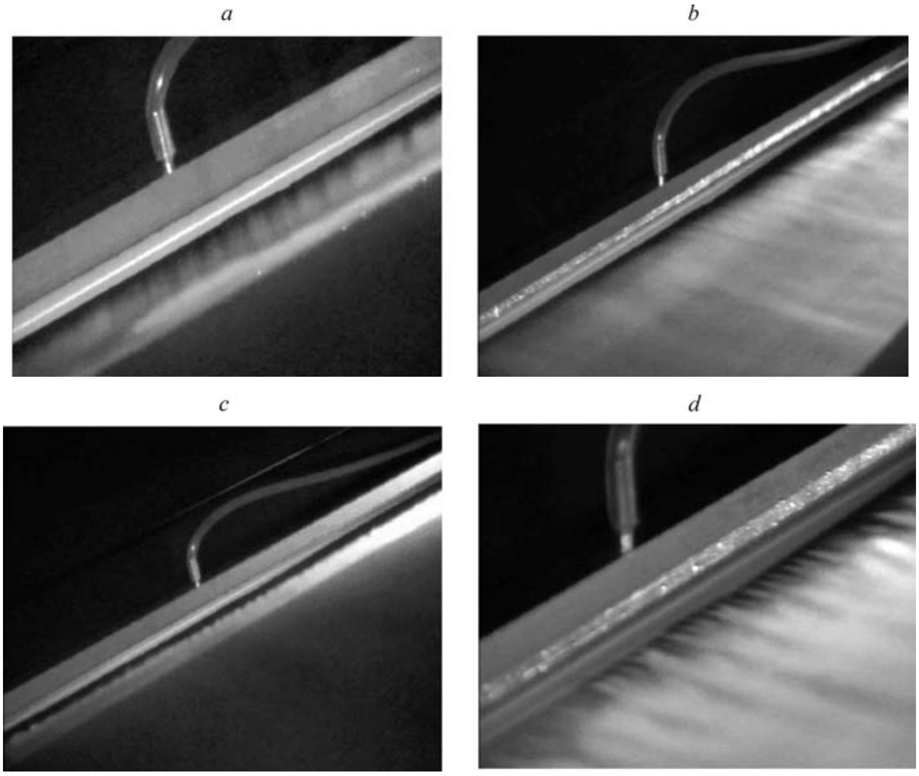

Fig. 11. Streamwise streaks created in the free shear layer by the roughness elements and forcing of flow at frequency 200 Hz (*a*, *b*), 700 Hz (*c*, *d*).

structures. The interaction of those two instabilities could speed up the jet-turbulization rocess. In Fig. 10, two most distinguished cases are compared when forcing frequency was 200 Hz (*a*) and 700 Hz (*b*). In Fig. 11, the flow visualization for these two cases are shown. When 2D instability at frequency 200 Hz was artificially forced, the three-dimensional effects were less pronounced, and the flow turbulization had almost pure two-dimensional character, while at forcing frequency of 700 Hz, the three-dimensionality was most obvious, and well-defined three-dimensional structures were observed in the process of breakdown.

CONCLUSIONS

1. Detailed hot-wire measurements and smoke visualizations have shown that the longitudinal structures in the plane wall jet can be generated directly from the nozzle outlet.

2. It is established that the transverse size of the roughness elements and longitudinal structures is correlated. In particular, the size of longitudinal structures in the boundary layer is two times larger than in the free shear layer, probably because of different stability for these layers.

3. Artificial excitation of two-dimensional Kelvin — Helmholtz waves of different frequency has an influence on transverse size and amplitude of longitudinal structures. Interaction of two-dimensional instability with three-dimensional streaky structures can delay or accelerate the turbulization process in the jet.

4. From results of the smoke visualizations and hot-wire measurements it was established that the jet exit Reynolds number increase leads to the acceleration of the jet breakdown and to decrease in the characteristic size of the longitudinal structures due to decrease in the thickness of the shear layers.

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