A Visualization Study of the Longitudinal Structures of a Plane Wall-Jet

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Abstract: 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. It was found that the value of outlet velocity and the frequency of Kelvin-Helmholts rolls have a clear influence on the size of the structures. Higher outlet velocities and higher frequencies of triggered two-dimensional roll-ups lead the size of longitudinal structures to decrease.

Keywords*: plane wall-jet, longitudinal structures, hot-wire measurements, smoke-visualization*

1. Introduction

A turbulent wall-jet may generally be considerate 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 automobiles 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-Helmoltz 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 originates from an internal instability of the primary vortices. Experimentally it was found, e.g. in [2] and [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 than they penetrate into cores. The same result was obtained by [4], who pointed out the importance of the streamwise vorticity in the mixing process and formation of internal structure of flow in the near field of circular jet. The experimental investigations of the free shear flow are supported by many numerical studies, among these [5], [6] and recently [7] reveal 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.

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 this curved-wall flows have been shown to be unstable with respect to a streamwise motion. [8] studied curved wall-jet on the concave wall, and [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 believed, that on a curved surface the vortices are associated to the centrifugal instability.

In the current 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 point 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 numerous measured instantaneous velocities.

2. Experimental methods

2.1. Plane wall-jet facility

All experiments were conducted at Chalmers University of Technology and in the wall-jet facility, as is 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 the Fig. 1 with *X* in the streamwise-, *Y* in the normal- and *Z* in the spanwise-direction. Equipped with a vertical backwall (height 1.2 m) placed over the inlet and side walls, the current wall-jet can be considered to operate in quiescent surroundings, since the wall-jet facility is located in a large hall (15 × 15 × 8 m) with negligible room draught as compared to the wall-jet velocity.

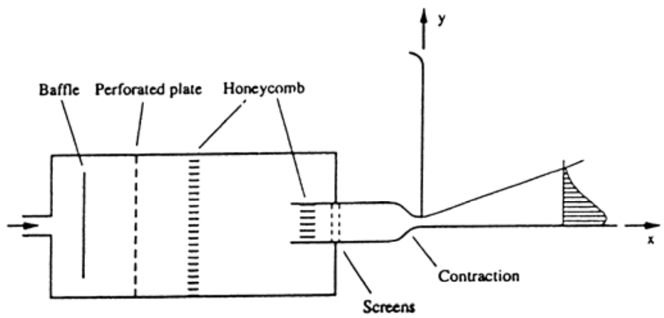


Fig. 1. Wall-jet facility

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 10:1), see Fig.1. The outlet turbulence level is sufficiently low, of order 0.1%. During the measurements, the velocity in the middle of the inlet, U_j, is controlled by the Prandtl tube.

2.2 Measuring techniques

The streamwise velocity component was measured by hot–wire driven by a DANTEC constant temperature anemometer (mini CTA). A tungsten single wire boundary layer probe with a wire diameter and length of 5 μm and 2 mm was monitored at overheat ratio of 1.3. The hot-wire was calibrated in the jet outlet versus Pitot tube. 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 a 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.

The hot-wire probe was positioned by accurate automated traversing mechanism. The traverse 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.

At the heart of the acquisition system is the IOTech Wavebook 516 sampling module with expansion unit. This enable 16-bit, 1 MHz, simultaneous sample and hold of 16 analogue and 16 digital channels with full analogue and digital triggering options, in a maximum range of ±12 V. The software used to control the sampling and save data files is also linked into a program for automated, triggered flow measurements using the traverse system and a pre-defined mesh of sampling points.

The two dimensional waves in the wall jet flow were excited by a loudspeaker situated about two meters from the outlet. Sinusoidal disturbance of controlled frequency and amplitude were generated by DA board in a computer.

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.

3. Near field of the wall-jet under natural conditions

The natural condition is here defined as a flow without any additional artificial roughness-elements and without excitation by sound. Qualitative data on the onset of the streamwise vortices near the outlet of a plane wall-jet were obtained from the flow-visualizations and mean flow properties from hot-wire measurements.

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

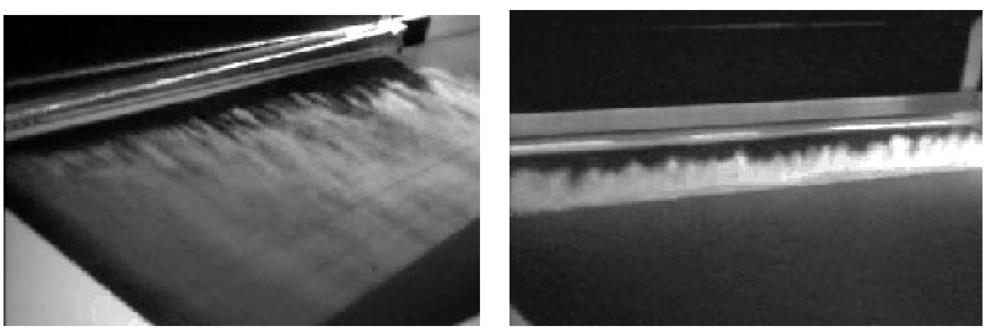


Fig. 2. Smoke visualization of the wall-jet flow under natural conditions in *XZ*-plane (left) and *YZ*-plane (right). Jet nozzle is located at the background

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. Figure 3 presents measurements of the mean velocity for the 2D part of the wall-jet near field. The mean velocity profiles at the different streamwise positions are shown in these figures and it may be noticed that the mean velocity profiles are self-preserving when scaled in appropriate way. In the near wall region measurements reveal that flow is initially laminar and 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.3, left) 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.

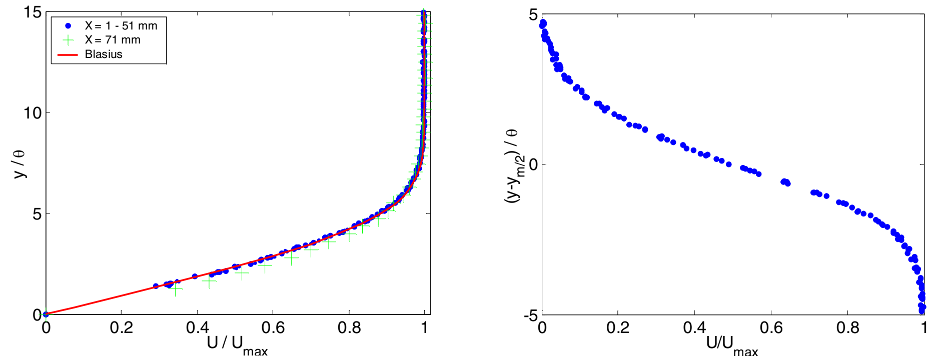
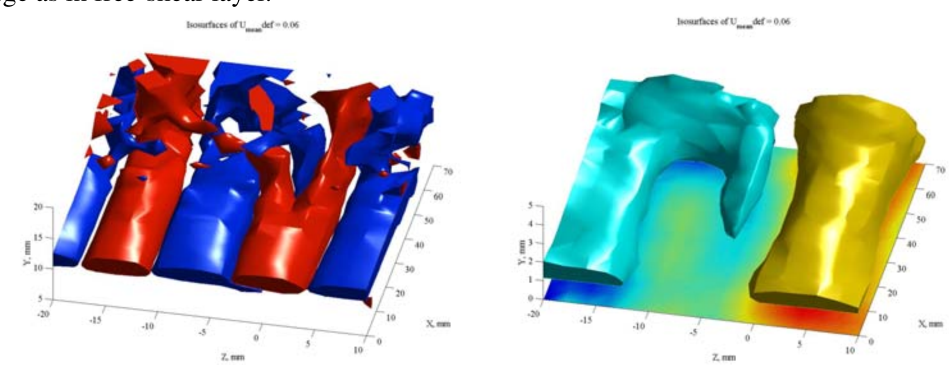


Fig. 3. Mean velocity profiles in the near field of the wall-jet. In the near-wall region profiles initially close to Blasius (left) and the top part of the wall-jet reveals typical shear layer profiles (right)

4. Hot-wire study of artificially generated streaks

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 allow 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. Stabilized three-dimensional flow field pattern was studied in detail by hot-wire mapping.

The hot-wire results obtained with the roughness-elements are shown in Fig. 4a,b where the free shear layer and the boundary layer of the wall-jet are shown in a grid of 3120 points each. The streamwise structures, which occur naturally in these layers, have different spanwise scales emerging at different distance from the nozzle. It was found that artificially triggered in the free shear layer streaks also stabilize the disturbance pattern in the boundary layer but in this case eigen spanwise scale in boundary layer is different and Fig. 4b shows naturally occurring pattern in the wall-shear layer. This two figures show isosurfaces of the mean velocity defect/excess relatively to the averaged in spanwise direction mean velocity. It should be noted that Y-axis in Fig. 4b is three times stretched comparing to Fig. 4a. It can be seen that the characteristic spanwise scale near the wall is about twice as large as in free-shear layer.



a b

Fig. 4. Free shear layer. Isosurfaces of the mean velocity defect (blue) and excess (red) show artificially generated streaks (a). Boundary layer. Isosurfaces of the mean velocity defect (light blue) and excess (yellow) (b). Pseudo color plot at the bottom shows closest to the wall slice. Note that *Y*-axis is 3 times stretched comparing to Fig. 4a.

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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. Onto the inner surface of the nozzle 4 roughness-elements of each size were positioned 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.

Figure 5 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 24336 points with the same spatial resolution as in Fig. 4a. 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. From downstream coordinate of about 30 mm an intensive grow of Kelvin-Helmholtz 2D vortices occur resulting in flow changes and characteristic scale of 3D streaks also changes turning out to be smaller. More precisely the characteristic scales of streaks and their amplification rates were defined from flow maps using Fourier transform in spanwise direction, which in general supports qualitatively made conclusions.

The influence of the Reynolds number on the characteristics of the streamwise structures was also checked and visualizations similar to that in Fig. 5 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 the thinner shear-layer and hence the size of the longitudinal structures decreases as the Reynolds number increases.

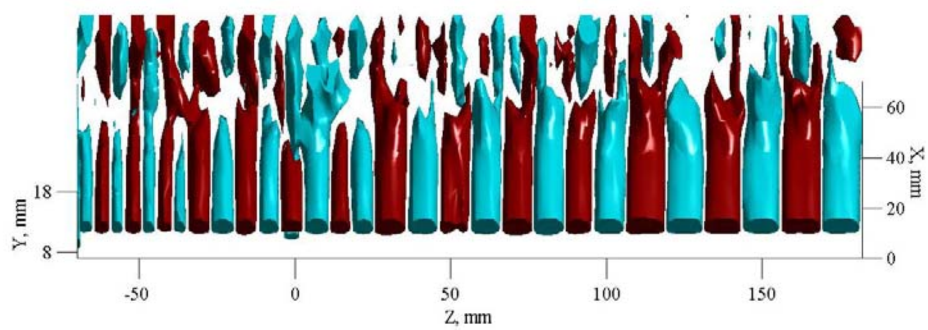

Fig. 5. Streamwise streaks created in the free shear layer by the roughness elements with varying periodicity. Isosurfaces of the mean velocity defect (light blue) and excess (red). Flow direction is from bottom to top

5. Streaks influenced by acoustic forcing

The artificial forcing of the Kelvin-Helmholtz instability in the free-shear layer of the wall jet allowed to study the effect frequency 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-Helmholts rolls have a clear influence on the size in transverse direction and amplitude of the streamwise vortical structures. The interaction of those two instabilities could speed up the jet-turbulization process. In figures 6 and 7 compared two most distinguished cases, when forcing frequency was 200 Hz (Fig. 6) and 700 Hz (Fig. 7). It the left part of the figures light sheet is parallel-to-the-wall (in *XZ* plane) and the right part of the figures shows the visualization in the cross plane (*YZ*). 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.

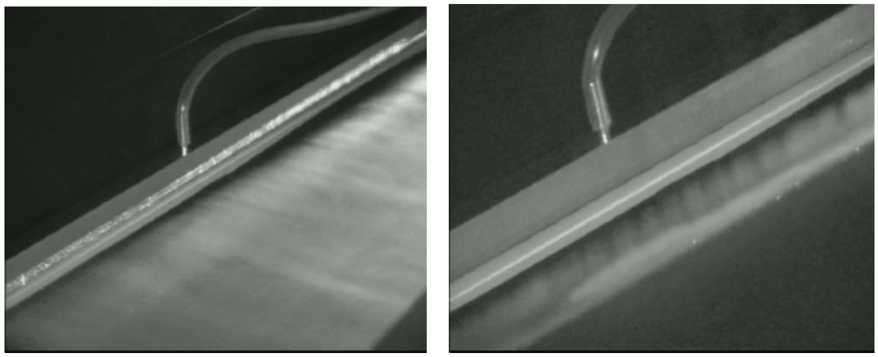

Fig. 6. Streamwise streaks created in the free shear layer by the roughness elements and forcing of flow at frequency 200 Hz

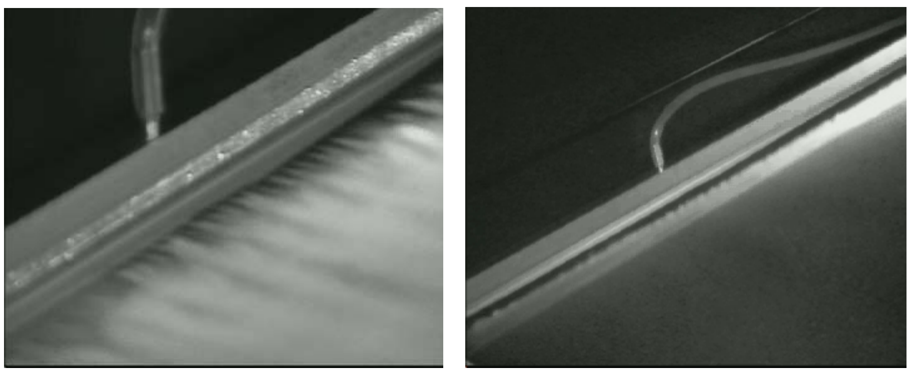

Fig. 7. Streamwise streaks created in the free shear layer by the roughness elements and forcing of flow at frequency 700 Hz

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