http://dx.doi.org/10.21611/qirt.2004.092

Coherent thermal structures in a turbulent channel flow

by D. Frontoso Silvestri, T. Astarita and G. Cardone

DETEC - University of Naples, P.le Tecchio, 80 - 80125 Naples, ITALY

Abstract

The thermal patterns that arise in a channel flow are analyzed experimentally. The experimental measurements are carried on by means of a non steady application of the *Heated Thin Foil* technique and by scanning the wall temperature by an infrared camera. The data processing is made by means of algorithms similar to the ones used in *Particle Image Velocimetry*. Different test conditions were performed and a comparison between them is presented, showing temperature maps, velocity histograms and autocorrelation coefficients.

1. Introduction

In a turbulent boundary layer the kinetic energy of the free stream is converted in turbulent fluctuations and then, on account of the viscous effects, dissipated in internal energy. In the absence of particular stabilizing effects this procedure is continuous, i.e. a turbulent boundary layer is self-sustained. The study of coherent and periodic structures is of fundamental importance in the understanding of the dynamics of turbulent boundary layers and, in particular, of the mixing in wall flows. A great part of the published investigations, that deals with coherent structures, are performed at low Reynolds numbers, where the range of turbulent length scales is limited, thus making easier both the numerical and experimental testing [1].

Various studies have shown that the near wall region has a complex structure due to the bursting phenomenon. Indeed the bursting is the major responsible for the production of kinetic energy in the inner layer and, hence, for the increase of the diffusive phenomena. Flow visualization experiments have shown that the bursts manifest themselves as strong perturbation of the wall region accompanied by intensive motion of the fluid away from the wall. Such motion seems to be a result of a powerful interaction of large-scale coherent structures with the elongated structures existing nearby the wall. The large-scale structures of the external layer generate fluctuations of pressure that propagate into the boundary layer towards the wall. These pressure fluctuations cause a deformation of the elongated structures near the wall that first break up and, then, eject low velocity fluid from the wall region, which is replaced by high velocity fluid from the external region. Where bursting occurs, the width of the viscous sublayer decreases by increasing the transport efficiency of passive scalars and, in particular, of internal energy.

Whilst in external flows many different types of coherent structures exist, in channel flows the major part of the structures is streamwise elongated (streaks). The formation of these structures is due to the action of streamwise aligned vortices that cause a transfer of low momentum fluid from the wall to the center of the channel and vice versa for high momentum fluid. The presence of these structures influences the turbulent statistics and, in particular, the spanwise correlation of the streamwise velocity component [2]. A passive scalar, and especially internal energy (or, what is the same in the present conditions, temperature), has a behavior practically identical to that of the velocity filed. It is thus expected that the thermal structures and statistics should behave in a very similar way. Really by using both numerical [3] and experimental methods [4] previous authors have already found thermal structures

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very similar to the ones of the velocity field. In particular, in a channel flow, with an imposed constant heat flux, it is possible to visualize cold and hot streaks in the temperature field at the wall. The characterization of these structures and the analysis of the temperature fluctuations at the wall, are useful in the optimization of the convective heat transfer flux between a solid wall and a fluid.

Aim of this work is to evaluate thermal correlations and the convective velocity field of the thermal structures at the heated wall. The study is conducted experimentally in a channel flow. The choice of such geometry allows having a statistic inhomogeneous flow only in the direction normal to the wall. The experimental measurements are carried on by means of a non steady application of the *Heated Thin Foil* technique and by scanning the wall temperature by an infrared scanning radiometer. By using this technique, it is possible to measure the temperature fluctuations at the wall, thus obtaining both visualizations and quantitative measurements.

2. Experimental apparatus and procedure

The experimental apparatus is represented in Fig. 1 and it consists of a straight channel with a rectangular cross section, a thermoregulation and a supply system. To reproduce a statistical two-dimensional case, the ratio between the width and height of the channel cross section is fixed to 5. By using water ($Pr \approx 7$) as a working fluid and without changing the Reynolds number, it is possible to reduce the characteristic turbulent fluctuations and convective times.

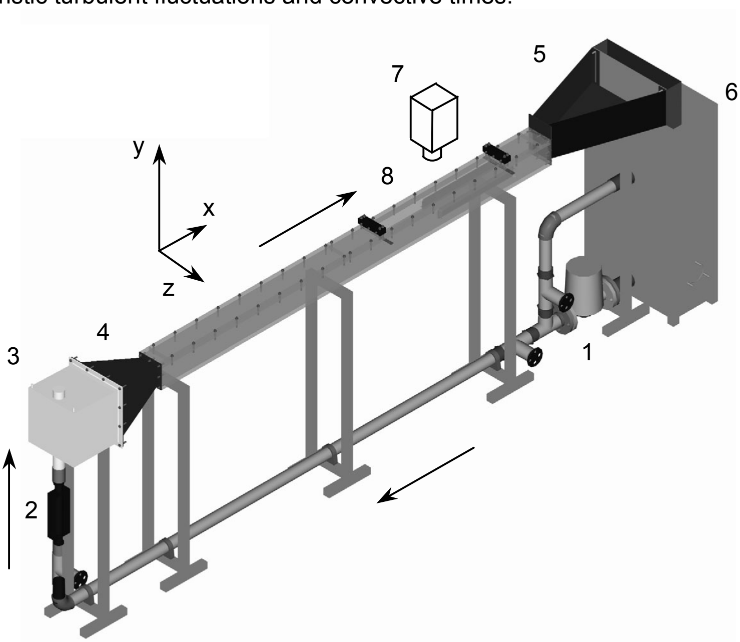

Fig. 1. *Experimental apparatus*

The channel is made of Plexiglas in order to have both a low thermal conductivity and good mechanical characteristics. The cross channel section is 20x100mm^2 and the overall length of the channel is 1.55m. In the final part of the channel, and for a length of about 800mm, the upper channel wall is substituted by a

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heating element in order to apply the *Heating Thin Foil* technique [5]. In particular this element is made of a thin (20μm) constantan foil that enables to have a practically constant thermal and electrical conductivity. A stabilized DC power source supply electric current to the foil by means of two copper connecting terminals that ensure a constant distribution of the electrical tension. This system enables to have a constant heat flux boundary condition on the upper channel wall. The foil is pretensioned by a system of springs in order to thwart the thermal expansion effects, due to the increase of temperature. To increase the thermal sensitivity of the Infrared (IR) Camera the foil external part is coated by a thin layer of black paint with a high emissivity coefficient and, in order to reduce the electrochemical effects, the internal part is covered with a thin layer of insulating paint. The turbulent structures induce fluctuations on the convective heat transfer coefficient that, in turn, induces fluctuations on the wall temperature scanned by the IR radiometer. The maximum achievable frequency response is clearly dependent both on the thermographic system and the heat flux sensor. By making a rough approximation, the foil response time is proportional to the square of its width and inversely proportional to its thermal diffusivity. The chosen foil material and width allows to reach a frequency response of about 10*kHz*. The latter decreases a little on account to the two layers of paint.

The thermographic system used during the test is the FLIR ThermaCam SC3000; the camera uses a GaAs sensor based on the new generation technology Quantum Well Infrared Photon detector (QWIP). The sensor is sensible to radiations in the 8-9μm infrared window and the signal is digitized at 14 *bits*; the nominal sensitivity is better than 0.03*K* when the scanned object is at ambient temperature. The image is digitized in 240 lines of 320 *pixels* with a standard acquisition frequency of 60*Hz*. The latter may grow till 900*Hz* by reducing the number of lines acquired.

Recalling Fig. 1, a recirculation pump (1) insures the water motion and a bypass enables to control the flow rate, which is measured by a rotameter (2). The water, before arriving in the channel, is convoyed in a settling chamber (3), where some filters reduce the turbulence, and then in a convergent nozzle (4). At the channel exit the water is collected in a first diverging open tank (5) and then, after a weir, it is poured in a second tank (6). The thermoregulation system, which is placed in the second tank, uses an electrical resistance for heating and tap water for cooling. The IR camera (7) is mounted on a traversing system, in order to frame the test section (8), namely the constantan foil.

3. Data processing and validation

By using the infrared camera, it is possible to obtain instantaneous thermal maps at the wall that may be successively analyzed by algorithms similar to the ones used in Particle Image Velocimetry. In particular it is possible to extract two temperature maps at a small time difference in order that the great part of the thermal structures are present in both the two successive thermal maps.

The algorithm to process the thermal maps is based on a multigrid iterative procedure with deformation of the images [6]. In the first step cross-correlation of corresponding interrogation windows is performed so as to find a predictor of the displacement field. In order to decrease the computational time, the correlation maps are evaluated by using the Fast Fourier Transform. It is possible to use different weighting functions during the evaluation of the cross-correlation map in order to increase the spatial resolution [7] and, to achieve sub pixel accuracy, the peak in the cross-correlation map is interpolated by using either a standard gaussian fit over the nearest five points or an iterative gaussian fit over the nearest nine points. In the successive steps the interrogation windows dimensions may be reduced until the

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final ones and also overlapped interrogation windows can be used. The predicted displacement field is interpolated over the whole image in order to perform the deformation of the images. The images are deformed symmetrically in order to have the displacement field vectors on a structured grid. The deformed images are finally elaborated by the same method explained for the first step. By using this algorithm, it is possible to evaluate the displacement field between two successive thermal maps and, by knowing the time interval and the spatial resolution, it is possible to evaluate the velocity field. PIV algorithms normally deals with particles randomly distributed in the interrogation windows while, in the present case, streaks are present and, as also stated in [4], this may produce a degradation of the accuracy.

In the following all symbols with a subscript + will indicate a non dimensional quantity scaled by the wall variables: $u_* = \sqrt{\tau_o / \rho}$, $y_* = \upsilon / u_*$, $T_* = q_o /(\rho c_p u_*)$ where τ_o is wall stress, ρ the density, υ the kinematic viscosity, T the temperature, c_p the specific heat at constant pressure and q_o the wall heat flux. With the aforementioned technique it is possible to evaluate the temperature autocorrelation coefficient:

$$R_{T'T'} = \frac{\langle T'(x,z)T'(x,z+\Delta z)\rangle}{\langle T'(x,z)T'(x,z)\rangle} \tag{1}$$

where ' indicates the fluctuating part and $\langle\rangle$ indicate an average in time and in the *x* and *z* direction, the coordinate system being defined in Fig. 1.

4. Visualization of the wall thermal field

The Reynolds number *Re* is based on the bulk velocity and on the half height of the channel; its effect on the wall temperature maps is shown in Fig. 2, where some experimental results ($Pr \approx 7$) are reported. The maps on the top are extracted from the same sequence of images (*Re*=2600), while the lower ones are randomly taken from tests made at *Re*=1850 and *Re* =8000 respectively. The flow direction is from left to right; white levels indicate high temperatures while black levels low temperatures. The streaks are clearly visible and one can discriminate cold structure from the hot ones. In some cases, it is possible to see a bifurcation of a single structure in two smaller ones and this effect is more evident by looking at a sequence of subsequent thermal maps. This situation is reported in Fig. 2 for the test made at *Re*=2600, where one can also follow the history of the streaks, as indicated for example by the rounded lines, which emphasize the same streak but in two different time instants. By decreasing the Reynolds number the structures, as expected, become bigger and less frequent; of course the opposite happens by increasing the Reynolds number. In particular, at the highest *Re* they appear very small and tortuous.

5. Results and discussion

Fig. 3 shows the experimental temperature spanwise spatial autocorrelation coefficient for two cases: *Re* =2600 and *Re* =5000. The streaks mean spatial distance Λz_+ can be evaluated as the double of the distance between the absolute maximum and the first minimum. For *Re* =2600 Λz_+ turn out to be near 125, while for *Re* =5000 is a little more than 180; for all the experimental campaign it was observed

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that increasing *Re* number leads to higher Λz_+. In order to discuss this trend, the dimensional peak location Λz is reported in Fig. 4 as a function of *Re* number.

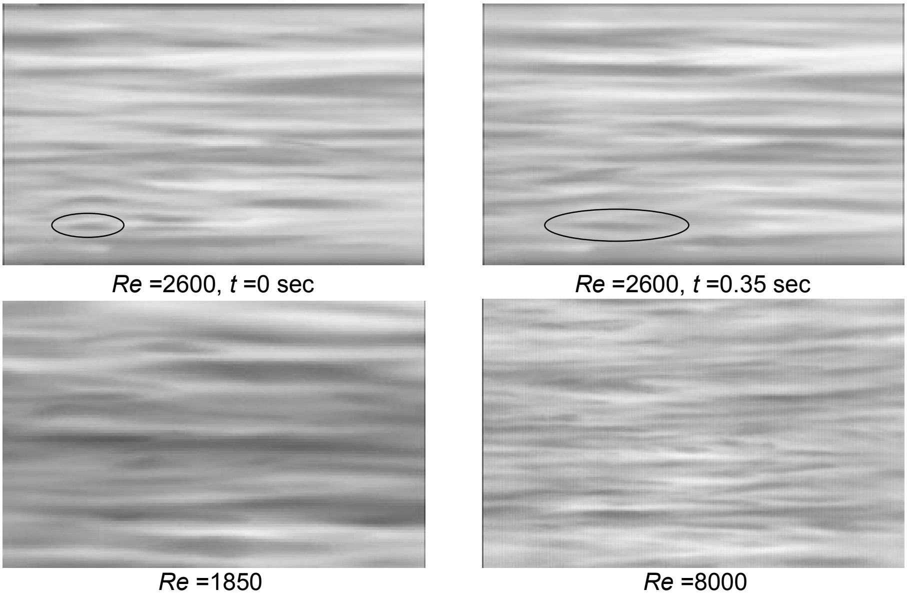

Fig. 2. *Experimental wall temperature maps*

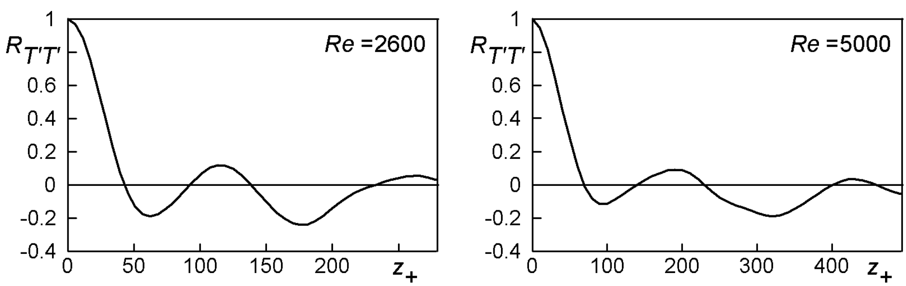

Fig. 3. *Spanwise wall autocorrelation coefficient $R_{T'T'}$ for Re=2600 and for Re=5000*

In Fig. 4 each point is the mean value of six tests made at the same *Re* number and Λz decreases with it. This means that for high *Re* number flows the range in which the variables are well correlated decreases, namely the decrease of the turbulent scale y_* is higher than the increase of Λz_+. These values are in good agreement with the numerical data reported in [3] and with the turbulent phenomenology that foresees smaller turbulent structures with increasing *Re* number. Knowing the location of the peak is important since it gives the dimension of the streak in the spanwise direction; this allows the quantitative rebuilding of the thermal structures in the interrogation window.

Finally the local streamwise convection velocity for the temperature coherent structures is analyzed by means of the described PIV algorithm. In Fig. 5 it is shown the histogram relative to the test made at *Re* =2600, for which several couples of thermal maps have been employed. The velocity distribution is quite huge and shifted forward low velocities with respect to the bulk velocity, the mean value being 2.20;

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this is most probably due both to the fact that close to the wall the flow is slower and to the elongated shape of the streaks that tends to fill the whole field of view of the camera, thus estimating smaller shifting.

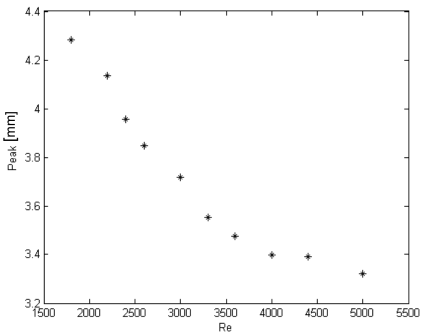

Fig. 4. *Correlation peak mean location*

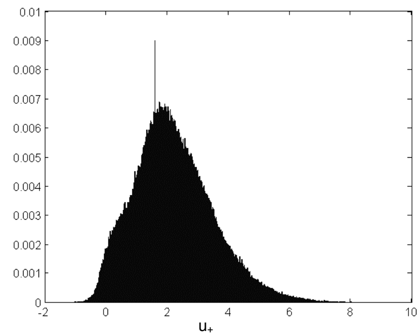

Fig. 5. *Histogram of the streamwise convective velocity*

6. Conclusions

A preliminary study of the thermal structures that arise in proximity of the wall, in a turbulent channel flow, has been conducted by means of an experimental approach. The choice of such geometry allows having a statistically inhomogeneous flow only in the direction normal to the wall. The experimental measurements have been carried on by means of an unsteady application of the *Heated Thin Foil* technique and by scanning the wall temperature by an infrared scanning radiometer.

The wall thermal maps have clearly shown coherent cold and hot structures that are streamwise elongated (streaks) and an analysis of their convective velocities has been carried on. A Particle Image Velocimetry approach between successive thermal patterns has been used for the determination of the convective velocities. The distance Δz between two points for which temperature has to be correlated decreases for increasing *Re* number and this means that the turbulent structures become smaller and more frequent.

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