TRACKING OF THERMAL STRUCTURES FROM INFRARED CAMERA BY PIV METHOD

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ABSTRACT

The paper deals with measurements of convective velocity of large-scale thermal structures, using the thin foil technique and infrared thermography to visualize the thermal pattern on the wall. An image correlation method is proposed to track displacement of the observed thermal pattern. The idea of the method is similar to that of Particle Image Velocimetry (PIV), but the thermal patterns on the heated wall are used instead of tracing particles. On this basis, the thermal patterns created by the coherent structures of turbulent channel flow are examined. The proposed technique appears to be an attractive alternative for non-intrusive analysis of turbulent flow, especially in all cases, where opaqueness of channel walls excludes the use of optical methods.

1 INTRODUCTION

The typical transition to turbulence gives rise to large-scale coherent structures, defined as persistent flow patterns with a relatively large lifetime and spatial extent. Their identification, classification and analysis became an important element of turbulence investigations today. One of the possible methods to visualize the presence of such structure is the use of thermographic means to analyse temperature distributions on the wall bounding the flow. The idea is based on the assumption that coherent structures are the hydrodynamic origin of coherent thermal structures on the heated wall [1]. The knowledge of the convection velocity of these coherent structures can provide useful information on the various transport properties.

The convection velocity of the temperature fluctuations was found to be closely related to the convection velocity of the streamwise velocity fluctuations. For fluids characterised by relatively small thermal diffusivity (high Prandtl number), it is reasonable to assume that the convection velocity of temperature and velocity fluctuations are about the same throughout the boundary layer. If the temperature differences within the boundary layer are kept small, the buoyancy effects can be neglected. In such a case, the thermal pattern convected by the flow behaves in a similar way as an ink dye (passive scalar) used for the flow visualization, reproducing its main features [2]. The idea for the present study is based on the assumption that observations of this thermal pattern at the wall may reflect characteristics of coherent structures of the flow. The quantitative visualization of the transient thermal fields can be made using infrared scanning thermography [3].

The objective of the present study is to apply recent advances and improvements in the technique of Particle Image Velocimetry (PIV) to the analysis of behaviour of the temperature field observed on the channel wall. The goal of the present study is to determine whether the alternation of thermal streaks measured at the wall can be correlated with the main flow features. It is important to understand that, unlike classical PIV technique, our method attempts to track thermal patterns appearing as large objects of unclear and variable boundaries. It appeared that traditional correlation technique might be successfully applied to evaluate such images. However, due to the

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limitations typical to the FFT based PIV methods, the resulting displacement field is quite sparse with a number of spurious vectors generated. Further improvement in tracking motion of irregular flow features was obtained applying optical flow algorithm [4].

The present article describes our efforts to analyse sequences of infrared images taken on the heated bottom of the flume. Our preliminary experiments indicate that the analysis of the thermal patterns created by the coherent structures of turbulent channel flow, can become useful tool for both qualitative and quantitative data collection on the boundary layer flow properties in a variety of channel flow problems.

2 EXPERIMENTAL

The experimental setup for investigation of temperature fields of the heated surface is shown in Fig. 1. It includes an open flume [5], consisting of a rectangular stainless steel channel (4.3m long, 0.32m wide and 0.1m deep), entrance and exit tanks and a pump forcing circulation of constant temperature water. The flow depth is 0.037m and the hydraulic diameter is 0.066m. Care was taken to eliminate vibration, wave formation at the inlet and reflections from the outlet. A fully developed flow was established in the region beyond 2.5m downstream from the inlet of the flume. The measurements of the water velocity profile both and the distribution of the root-mean-square (r.m.s.) values of streamwise velocity fluctuations confirmed this. The measurements were done at the centerline of the flume, i.e., at $z = 0$. Velocity measurements were done by means of a hot film anemometer. The standard 90^{o} conical probe was connected to a traversing mechanism with a spatial resolution of 10µm. The measured value of average streamwise water velocity was $U = 0.25$m/s. The experimental value of shear velocity u^{*}=0.0133m/s agrees well with the "logarithmic law of the wall": $U^{+} = 2.5\ln(y^{+}) + 5.0$.

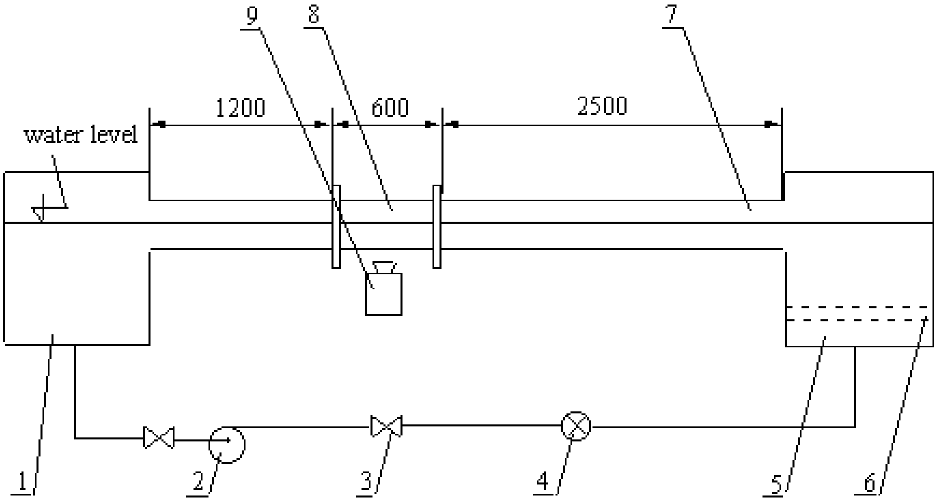

Fig. 1 A schematic diagram of the experimental facility. 1 – outlet tank, 2- pump, 3- control valve, 4- flowmeter, 5- inlet tank, 6- grid, 7- open channel, 8- test section, 9- IR camera.

The heated test section, at the bottom of the flume, was made of a constantan foil, 50µm thick, which was located at a distance of 2.5m from the channel entrance. The temperature distribution on the wall can be considered as a trace of the flow structure near the wall, i.e., the structures in the turbulent boundary layer are the ones that cause the temperature variation on the wall, including the thermal streaks. The experiments were carried out at a constant heat flux from the heated foil.

Throughout this paper, x, y and z denote the streamwise, wall-normal and spanwise directions, and U, u, u_V and w, w_V denote mean flow velocity and convection velocities of thermal pattern, or velocity fluctuations, in the streamwise and spanwise direction, respectively. Velocity is normalized by wall units as $U^+ = U/u^*$.

The image acquisition system consisted of an infrared scanner, S-VHS video recorder, computer, monitor and 8-bit frame grabber. The radiometer has a typical minimum detectable temperature difference of 0.1°C, a time response of 25 frames per second and a horizontal resolution of 256 physical pixels per line. The radiometer was located at a distance of 0.5m and the IR image created on the foil was recorded from below. The foil was very thin (50µm), and had negligible thermal inertia. It was shown [5] that the temperature difference between the two sides of the foil is of about 0.1°C and the frequency response of the system is about the same as the acquisition frequency of the IR camera. Therefore we may assume that the thermal pattern observed by the camera corresponds to temperature fluctuations in a thermal boundary layer of the flow.

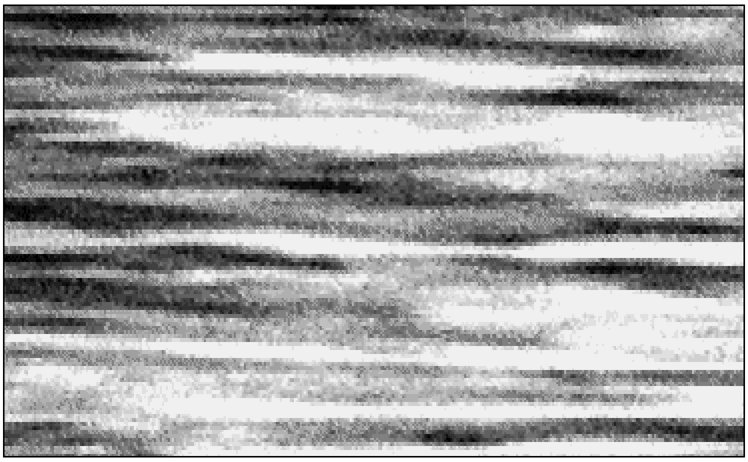

Fig.2 Instantaneous temperature distribution observed by IR sensor on the bottom of the flume in turbulent flow. Movie shows sequence of 16 images taken every 40ms. The gray level variation corresponds to temperature variation from 20.9°C to 22.9°C. Thermal pattern of the images covers area 170mm (width) x 130mm (length) of the foil.

The image had 256 intensity levels and was recorded on video tape of the S-VHS format as a conventional "interlaced" video scan pattern of 25 frames per second. The video was then used in a playback mode to analyze the data. The video frames were captured, digitized using the DT-3155 frame grabber and stored as 768x576 pixels images with the 256 intensity levels. Each image sequence contained up to 50 frames. The digitized images were subsequently analyzed by an image processing software. Once a set of picture data had been digitally captured and stored, the result was a succession of 50 sequentially recorded image frames depicting the temperature field on the foil at discrete instances in time. The incoming video signals representing IR images were transformed pixel by pixel into intensity maps (Fig. 2). The digitized image has size of 768x576 pixels, whereas the useful area representing thermal image covers 740x450 image pixels. Temperature was determined by relating the 256 gray levels to the temperature calibration function of the IR detector. Extracting image features found within selected gray level bandwidth, regions of specified temperature were filtered out.

The spatial correlation method implemented in the analysis of the experimental data is one in which the temperature correlation coefficients are obtained on point-by-point basis. This correlation coefficient is a measure of the similarity between the two temperature fluctuation signals. Instead of identifying discrete spots and tracking them from one image to the next, two-dimensional correlation between thermal patterns found within the analyzed windows were used to determine convective velocity of a thermal pattern. It allows for an identification of the trajectory of the thermal spots. To evaluate displacement of the thermal spots, initially the typical FFT based Particle Image Velocimetry (PIV) approach was used. In the implemented PIV technique [6] pairs of images to be correlated are obtained using a full video frame. Hence, a minimum time delay between images was Δt=40ms. By considering pairs of frames in a sequence taken at longer time steps this time interval can be easily increased. Small sections of both images, called *interrogation windows*, are cross-correlated and the average spatial displacement of the particles is evaluated. The mean displacement is provided by the position of the cross-correlation peak. The velocity in the interrogation window is obtained by dividing the displacement by the time interval Δt. The relative amplitude of the cross-correlation peaks with respect to the noise level is an indication of the measurement quality and is used as a criterion for the velocity vectors validation procedure.

Interrogation windows of 64 x 64 and 128x128 image pixels, 50% overlapped, were used to evaluate thermal spots displacement. The mean displacement is determined with a resolution of up to 1 pixel through interpolation, corresponding to about 0.24 mm for the physical size. The minimum velocity u_{min}, which the system is able to resolve, is given by the ratio between the minimum detectable displacement of thermal spots and the time interval Δt. For the pair of subsequent frames we obtain u_{min} = 6mm/s. This value can be considerable reduced by selecting pairs of images taken at longer time interval Δt within the same sequence. In fact, for a sequence of 50 images, a theoretical limit for the velocity u_{min} becomes 0.12mm/s. The maximum reliable displacement detectable by FFT based PIV evaluation is limited by the dimension of the interrogation window. In practice it does not exceed 0.5 of the interrogation window size. For a 128x128 pixels window, it corresponds to a maximum resolvable velocity u_{max} of about 0.35m/s.

The IR image created on the wall differs significantly from that created by seeding with particles used to evaluate flow velocity by PIV method. Instead of discrete dots we observe large spots covering the image. The velocity vectors must be determined for each thermal spot displacement, representing its mean evolution in time. For two-dimensional cases this could be directly correlated with the convective components of the flow velocity fluctuations. However, the coherent wall structures consist of high velocity regions and low-speed streaks very close to the wall. This configuration is periodically disturbed by ejections from the wall layer into the outer flow and sweeps back to the wall, generally referred to as “bursts”. Kaftori et al. [6] suggested that this pattern could be described as an expanding spiral, wound around a funnel that is laid sideways in the direction of the flow. These velocity fluctuations produce strong modulation of the temperature field in the wall layer. Hence, size and intensity of the thermal spots observed at the wall varies in time. This effect is similar to the appearance and disappearance of particles crossing an illumination plane for classical PIV. It causes a broadening of the cross-correlation peak, reducing the overall evaluation accuracy. In our experiments the third velocity component becomes noticeable large in regions where the funnel vortices separate from the wall. The “out of plane” bursts deteriorate the temperature pattern, what is appearing as false velocity vectors in the PIV results. The typical validation approach of classical PIV procedures substitute such vectors by averages among the surrounding ones. In our case this approach is not acceptable. In fact the temperature field in such places is discontinuous. Hence, we rather leave raw results of the cross-correlation as they are, limiting our analysis to the regions granting high correlation coefficients. The remaining regions of low correlation factor could eventually be interpreted as possible locations of turbulent bursts.

As already mentioned, images of large thermal spots radically differ from the images typical for PIV. This may seriously degrade accuracy for the typical FFT based evaluation procedure. Further improvement in quality and smoothness of the evaluated fields was obtained applying a method recently developed by Quénot et al. [4]. Using the Optical Flow (OF) algorithm, the method is free of the typical PIV limitations, still preserving high accuracy of the evaluated velocity field. The method is based on the search of a transformation that relates the second image to the first one by minimizing the distance between them. The matching is performed iteratively, starting from several parallel overlapping strips sliced from the both images. For every pair of strips an optimal match is searched. The continuous matching of the image texture used by the method, in contrary to the classical PIV method, does not need quasi-periodic image structure produced by a particle flow seeding. Hence, seemingly to Image Correlation Velocimetry, the method is well suited to analyze particle-less images.

The ability of the PIV method to determine correctly an average value of convection velocity of thermal pattern has been tested using a thin heated wire moving along the channel (in the x-direction) [8]. The displacement of the thermal pattern recorded by IR camera was measured and compared with the known velocity of the wire. It was found that for investigated case, using 64x64 pixels interrogation windows, relative error for the streamwise velocity is 13%, The main source of error is believed to be due to the limited spatial resolution of the IR imaging system. Both shape and size of the thermal spots varies strongly as they are conveyed across interrogation window. Somewhat better result (8% error) could be obtained applying Optical Flow based PIV method of image evaluation. The method does not need any window adjustments and provides smooth velocity field with displacement vector calculated for each pixel of the image. In fact for images with a fine texture the spatial resolution of the method is limited by a camera resolution only. In our case it is limited by IR sensor to about 0.6mm. To improve accuracy several images of the sequence can be used simultaneously for displacement evaluation. In the present work best results were obtained using OF-PIV method with three subsequent images taken at 40ms interval.

3 RESULTS

In the following examples of measurements performed, we consider the flow of water at Re = 9200 with the mean flow velocity U=0.25m/s. The heat flux from the heated foil is $q = 12\ kWm^{-2}$, and Prandtl number Pr = 7.1, water temperature at the inlet is $20^oC \pm 0.1^oC$. The temperature variations in the range of 2^oC were observed at the wall section monitored using IR radiometer.

A typical sequence of the formation and development of the temperature streak starts with the rise of small moving high or low temperature spots. These spots change their position and streamwise length. Figure 2 shows sequence of IR images of the wall temperature taken at time interval 40ms. The high and low temperature streaks, clearly seen on the wall surface, indicate presence of the coherent structures advected by the main flow. The bright patches correspond to regions of higher temperature on the bottom of the flume. The streamwise flow structures persist some time until strong mixing (vertical burst) leads to their disappearance. The cold regions (dark streaks) indicate locations of the strong vertical motion (wall ejections and in-sweeps), which is responsible for the increased heat transfer. They appear to move faster and often overtake adjacent bright streaks. The high and low temperature streaks may interact with each other too. The present examination was concentrated on the downward moving spots of high temperature (bright range of gray levels), as they were thought to be associated with low-speed flow structures.

An example of evaluated propagation velocity for sequence displayed in Fig. 2 is shown in Fig. 3. The vector field was evaluated for the gray level band of 175-255 using OF-PIV procedure. We may note that the convection motion varies both in the direction as in the magnitude but a strong streamwise velocity bias transporting thermal spots from left to right is clearly visible. The contour plots in Fig. 4 show maps of two components of the velocity vector field. It can be seen in Fig.4a that the streamwise velocity preserves main features of the temperature strips. The propagation velocity varies from peak values close to 10u* to slightly negative values, where direction reversal of the spots motion were observed. Figure 4b shows the spanwise component of the hot spots velocity. Their mean velocity was close to zero and both negative and positive deflections of the motion form kind of the chessboard pattern in the contour plot.

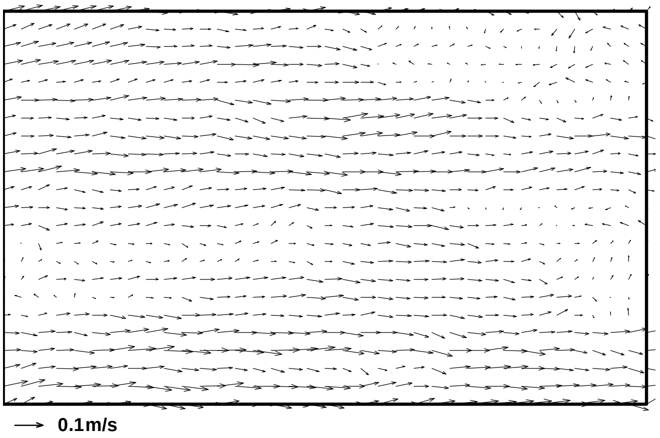

Fig. 3 Instantaneous velocity vector field of thermal spots evaluated from IR images shown in the previous figure. OF-PIV method, selected for evaluation gray level bandwidth: 175-255.

Figure 5 shows an example of the transient behavior of the pattern. The streak velocity at arbitrary selected point is extracted from the evaluated vector fields and plotted for a period of 1.2s. Displayed plots demonstrate well a striking feature of the temperature field on the heated wall in a turbulent flow, i.e. that coherent thermal structures (CTS) behave like pulses in time. It is significant that not only the z-component but also the x component of the convection velocity shows these eruptive events. The time variation of convection velocities, shown in Fig. 5, indicates that the convection velocity in the x direction is much higher than that in the z direction; thus, the observed structures are nearly aligned in the streamwise direction. Although the streamwise propagation velocity varies, its time average has non-zero positive value. It clearly indicates that the thermal pattern propagates in the streamwise direction. This motion is associated with the propagation velocity of the velocity fluctuations in the turbulent flow. The transverse component of the convection velocity w varies with time with nearly symmetrical positive and negative amplitudes, when analyzed for a longer time interval. In fact, the time and space averaged spanwise velocity of the sequence is close to zero.

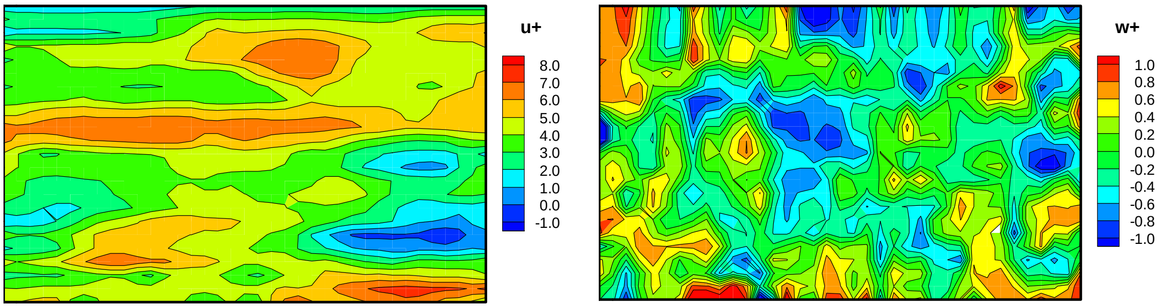

Fig. 4 Velocity contour plots evaluated from the instantaneous vector field of the convective velocity of thermal spots. Streamwise (left) and spanwise velocity component (right).

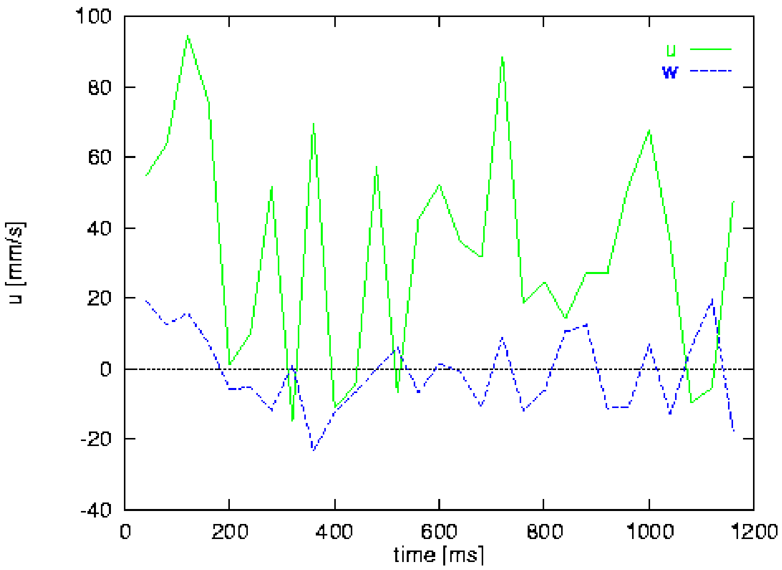

Fig.5 Time variation of convection velocity of coherent thermal structures on the heated wall extracted for an arbitrary point of the evaluated velocity vector field; solid line – streamwise velocity component, dashed line – spanwise component.

The streamwise velocity fluctuations are related to the geometry of the streak pattern. The low and high-speed streaks passing the selected point of observation contribute to the transient pattern. For sufficiently long observation time, their main characteristics will become space independent. Then, analysis of the full field temporal behaviour of both velocity components may deliver large amount of data for statistical analysis of the flow. But even our relatively short sequence may be used to evaluate characteristic velocity of the observed thermal structures. For this purpose we need to identify them in the velocity vector field. Looking at the velocity contour plots shown in Fig.4a, we may note red patches where high displacement velocity was found. We assume that they indicate the location of moving thermal spots. To evaluate their characteristic velocity, some discrimination technique must be applied. We arbitrary assume that centroid of pixels having a streamwise velocity above 85% of maximum velocity of the analysed field represents displacement of the hot spots. By taking the time and space average of such discriminated velocity values, the mean streamwise velocity component of the hot spots was calculated for the whole sequence. This value for the analysed sequence of 31 images was 0.127m/s. Hence, the upper limit of mean velocity of the temperature fluctuations on the heated wall obtained in the present study is $u_v^+ = 9.54$. The mean velocity is much lower and for investigated case equals 0.048m/s, i.e. 3.6u*.

As we mentioned before the thermal pattern recorded by IR camera exhibits longitudinal displacements of bright (hot) and dark (cold) spots (comp. movie in Fig. 2). It appears that their velocity is different, apparently the cold spots are moving faster. Remembering that the wall temperature strongly depends on the third velocity component (from or to the wall), this difference in the convective velocity can be used to discriminate different coherent structures acting on the wall. Figure 6 shows velocity histograms obtained for the sequence of 16 images separately for “hot and “cold” thermal spots. The hot spots were discriminated by gray level bandwidth 175-255 and the cold spots selecting the gray level range 0 - 100. Looking at the velocity histogram (Fig. 6) we may note that the measured streamwise velocity characterizes very broad spectrum with a flat maximum close to $u^+ = 4$ for the hot spots and slightly higher value for the cold spots. The corresponding mean value is $u^+=3.76$ and $u^+=4.77$, respectively. These values seem to coincide well with recent DNS simulation [9] for the channel flow of water. The mean propagation velocity of thermal fluctuations evaluated accordingly to Krogstad et al. [10] from this simulations is $u^+=3.24$ for the “hot” (sweep), and $u^+=5.60$ for “cold” (ejection) bursts.

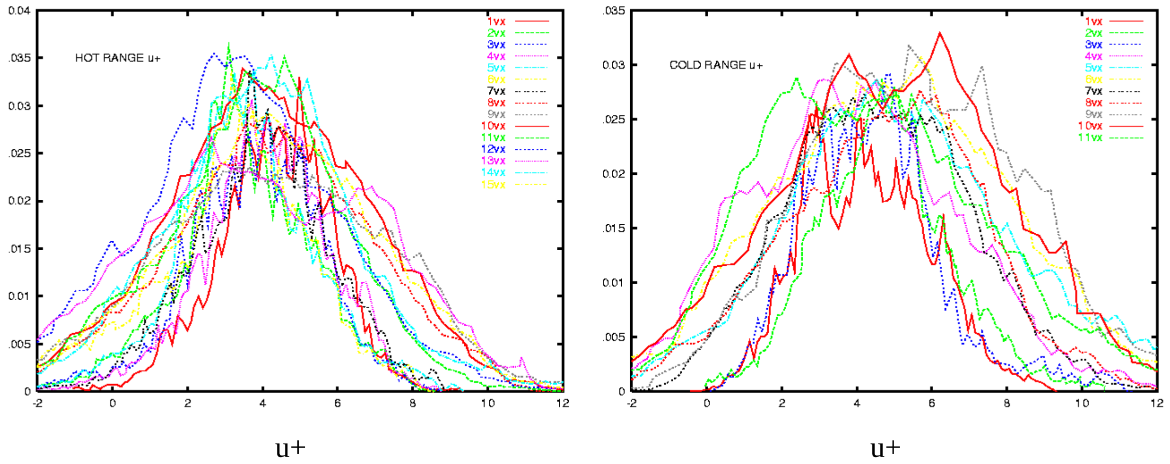

Fig.6 Histograms of non-dimensional streamwise velocity evaluated for a sequence of the IR images; left – hot spots evaluation, right – cold spots evaluation.

In order to clarify the correlation of the observed convective velocity of the thermal spots with the underlying large scale coherent structures in the boundary layer a sequence of numerically generated images was evaluated using procedure described above. For this purpose the temperature field calculated on the wall was used to generate gray level contours simulating the IR images. These synthetic images of the wall temperature show longitudinal structures similar to these shown in Fig. 2. By applying to these images the above-described PIV evaluation procedure the convective velocity of the thermal spots was found. Figure 7 shows histogram for the streamwise velocity obtained in such a way for a sequence of the synthetic images. It appears that most probable value of CTS propagation velocity is close to 4. The average streamwise fluctuation velocity calculated from these images was 3.8 for hot spots and 4.44 for the cold spots. It indicates strong correlation between measured propagation of the hot spots and the typical convective velocity of the turbulent velocity fluctuations. It appears to us that the most probable velocity of the thermal spots is the appropriate indicator for measuring the CTS propagation velocity.

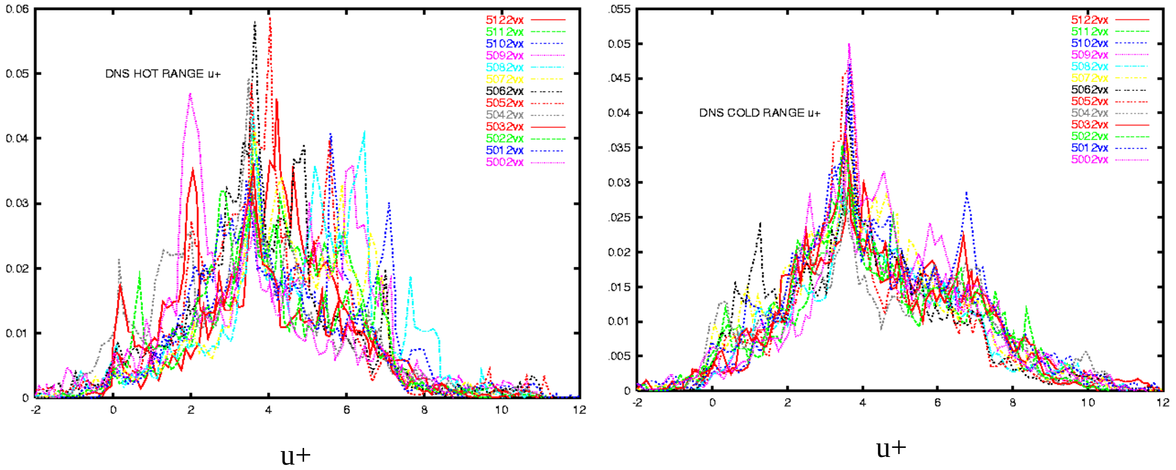

Fig.7 Histograms of non-dimensional streamwise velocity evaluated for a sequence of the synthetic images generated from DNS solution; left – hot spots evaluation, right – cold spots evaluation.

4 CONCLUSIONS

The present analysis demonstrates ability of the PIV based evaluation method to track the coherent thermal structures visualized on the wall by IR camera. The temporal and spatial analysis of long time sequences of thermal images may allow us to evaluated basic characteristics of the underlying fluid flow. It has been demonstrated that the mean convective velocity of coherent structures can be relatively well evaluated from the thermal pattern dynamics. It is worth noting that the method allows us to get this velocity without any optical or mechanical access to the flow. We believe that other scalar characteristics, like bursting period, mean turbulent energy and diffusion constants, can be correlated with the observations of the transient behaviour of the thermal pattern.

However, it must be considered that our observations are limited to two-dimensional projections of the flow structure and its quantitative interpretation needs additional information about the main flow. These experiments have only demonstrated the qualitative behaviour of the thermal streaks. Full field measurements of the main flow characteristics performed for various flow conditions combined with monitoring of the thermal streaks dynamics may provide a sufficient amount of data to build and verify models relating the turbulent flow characteristics with their scalar “finger prints” at the wall.

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