QUANTITATIVE VISUALIZATION OF THE NEAR-WALL STRUCTURES IN A FULLY DEVELOPED TURBULENT PIPE FLOW

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ABSTRACT
In this paper the quantitative properties of the near-wall structure in a fully developed turbulent pipe flow are investigated by DPIV and ICV techniques at Reynolds number 5500. The results show that the near-wall structure visualized by conventional dyes is dominated by ejection events. The quantitative measurements of velocity fluctuations inside the structure indicates the interpretation of flow visualization pictures should be with caution.

INTRODUCTION
The target of this study is aimed at the flow field inside near-wall structure of turbulent pipe flow. The near-wall structure has been visualized by the authors (Zhang et al 1998)[1], it has been shown that the flow structures are similar to those at flat wall-bounded turbulence with different average characteristics, for instance greater mean spacing of longitudinal vortices and longer mean periods of bursts. In the paper both visualization technique and quantitative measurements are used to investigate the flow characteristics inside the structure. DPIV technique is used to obtain the velocity fluctuations from particle images and ICV technique[2] for concentration images of fluorescent dye. It has been found that the local fluctuations inside structure are characterized by outflow motions, the quadrant analysis shows that the ejection events are dominant in the structure. The digitized velocity fluctuations disclose that the judgement of vortex from visualization should be with caution.

EXPERMENTAL FACILITY AND METHODS
The experimental facility is sketched briefly in Figure 1 and the details can be found elsewhere.[1] The fine particles of $3\mu m$ are induced to the near wall region from a narrow slot at the pipe wall for quantitative flow visualization.

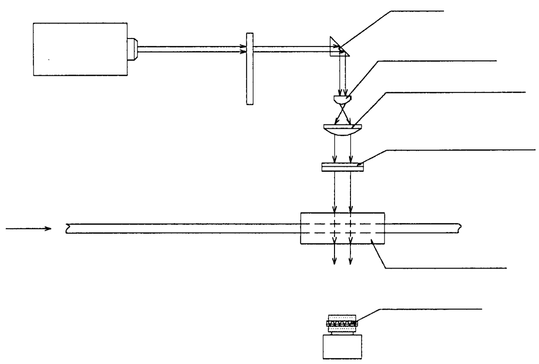


Figure 1 Schematic experimental set-up

The visualized pictures and particle images are recorded by CCD camera and then grabbed in PC for processing. To make sure that the particles are tracking turbulent flow perfectly, fluorescent dye and particles are induced simultaneously through a slot at the wall. Figure 2 shows that the particles are as good as the fluorescent dye for the visualization.

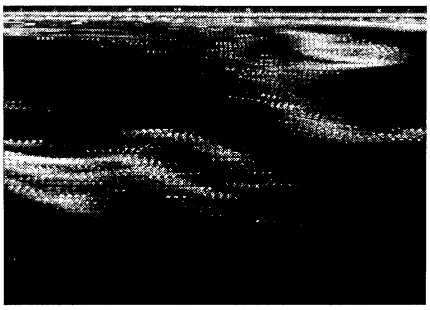
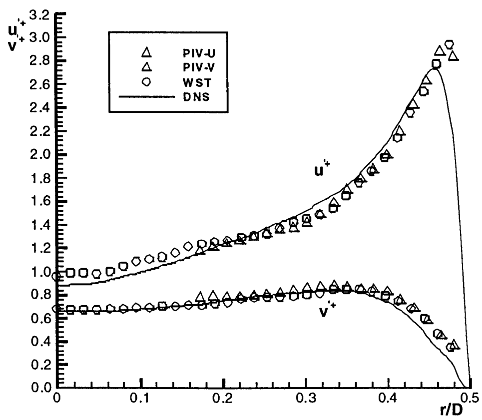


Figure 2 The visualization picture (dotts: particles)

Before quantitative visualization the turbulence properties have been measured by DPIV technique in order to confirm that the flow is fully developed turbulence and the DPIV system is appropriate.

The part of the results are shown in Figure 3 and it



is satisfactory for the test.

Figure 3 DPIV measurements of turbulence intensity, WST-Westerwell et al[3], DNS-Eggels et al[4]

The quantitative characteristics of the visualized structures are analyzed by the local average inside the structure as follows

$$\overline{U}_i(r)=\frac{1}{N_x^c}\frac{1}{N_t}\sum_{N_x^c N_t} u(x_n,r,t_n) \quad (1)$$

$$-\overline{u_i'u_j'}=-\frac{1}{N_x^c}\frac{1}{N_t}\sum_{N_x^c N_t} u_i'u_j' \quad (2)$$

In the above equations the summation index N_t denotes the number of the visualized frames in time series and N_x^c denotes the streamwise grid numbers inside the structures. Therefore the local average means that the velocity and its fluctuations outside of the visualized structure are excluded in the average.

THE RESULTS

The local mean velocity profile, shown in Figure 4, indicates that the local mean velocity inside the structure is smaller than the global mean. The Reynolds stress, demonstrated in Figure 5, show that local Reynolds stress is much greater than the global average in the region $y^+>15$. This implies that the visualized structure includes a generation process of turbulence with smaller streamwise velocity than global mean velocity. Therefore we can image that the visualized structure is dominated by ejection events. To confirm the conjecture we have made quadrant analysis of the local Reynolds stress as shown in Figure 6. It is clear that both turbulence intensity and Reynolds stress are contributed from the second quadrant, i.e. ejection events. In Figure 4 and Figure 5 the velocity and its fluctuations are scaled on the wall friction speed.

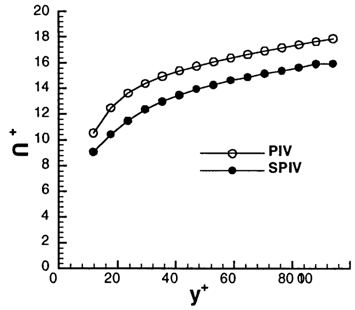


Figure 4 The local mean velocity.
PIV: global average; SPIV: local PIV

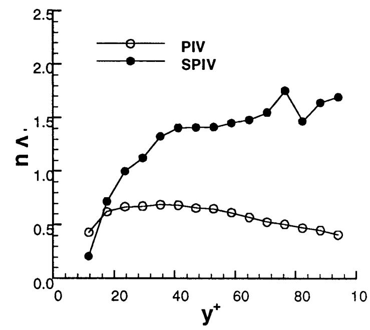


Figure 5 The local Reynolds stress.
PIV: global average; SPIV: local PIV

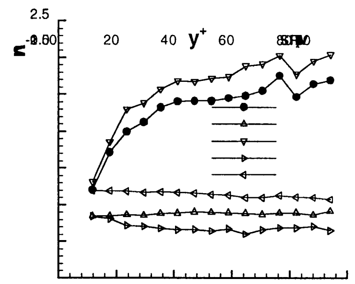


Figure 6 The quadrant analysis of Reynolds stress
(Number in bracket stands for the quadrant)

Usually the visualized flow pictures give us the global description of the flow structure, in particular the vortex structure, for instance the mushroom structures in dye are commonly interpreted as a vortex. However we have found that it is not always true. Figure 7a shows a visualized picture with two 'mushrooms' at A and B, Figure 7b is the quantitative results of the fluctuating velocity for the visualized image. It is clearly show that A is an eddy but B is not.

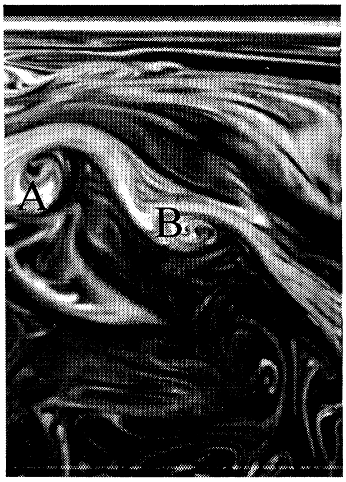


Figure 7(a) Visualized picture
Figure 7(b) Quantified fluctuating field of (a)

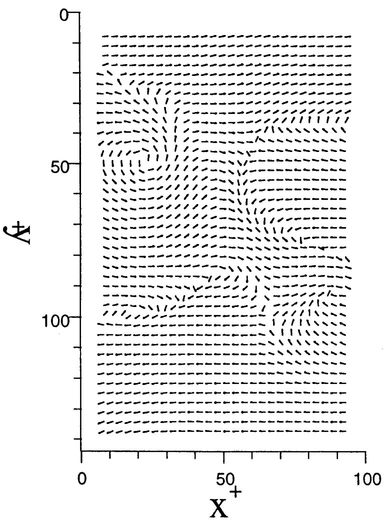


Figure 8 present the part of quantified fluctuating field of visualized picture demonstrated in Figure 2. The visualization picture by particles shows that there are rolling up structure at the interface, it is thought as an eddy usually. It is true in comparison with the quantitative fluctuating field. However an eddy exists underneath the interface, it usually can not be shown in visualized pictures.

CONCLUDING REMARKS

The authors emphasize the importance of quantitative visualization for both understanding of the flow structures and correct interpretation of the flow visualization.

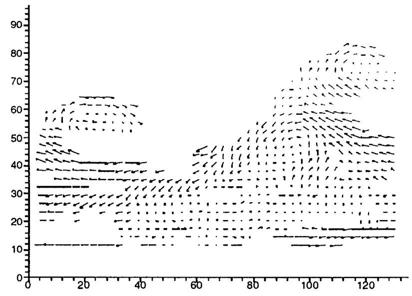


Figure 8(a) Instantaneous fluctuations inside the structure

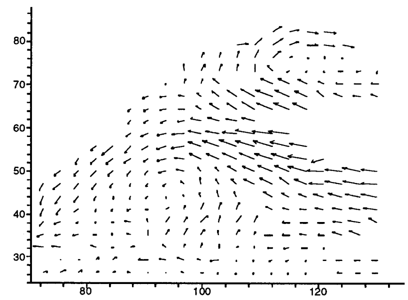


Figure 8(b)The enlarged upper right part of picture (a)

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