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FLOW VISUALIZATION OF EFFECTS OF WALL ROUGHNESS ELEMENTS ON NEAR WALL COHERENT STRUCTURES IN A CHANNEL FLOW

LU Hao, WANG Bing, ZHANG Hui-Qiang[1], WANG Xi-Lin

(School of Aerospace, Tsinghua University, Beijing 100084, China)

ABSTRACT

Using the hydrogen bubble flow visualization technology, the effects of wall roughness elements on the near-wall coherent vortices structures are studied in a channel flow. The roughness elements row is located on the bottom wall before the hydrogen bubble wire. The Reynolds number, based on the mean velocity and channel hydraulic diameter, is from 14299 to 48000, and the roughness elements are spheres with diameter of 2.3, 4, 5 and 6mm arranged at intervals of 2cm in the spanwise direction. The results show that the streak number, the vortex number and the vortex height increase with the Reynolds number both for the smooth- and roughness-wall cases. In the condition of same Reynolds number, the change of streak number and the vortex height with the roughness element sizes is nonmonotonic. The results are valuable to flow controls in engineering.

Keywords: wall turbulence, streaks, coherent structure, roughness, Reynolds number, hydrogen bubble flow visualization

1 INTRODUCTION

The generation, developments and broken-up process of coherent structures is the main energy exchange mechanism in turbulence. Since 1967, Kline et al has found the coherent structures of turbulent flows, many investigators have devoted themselves to the research. However, the investigations on the coherent structures of wall turbulence with roughness are still not enough.

Perry et al (1987)[1]carried out the research on effects of rough-wall on the turbulence and found that both the average velocity and the fluctuating velocity in the inner boundary layer with wall roughness increase, but keep constantly in the outer boundary layer, compared with the smooth wall flow. Krogstad, et al.(1992)[2-3] however found that the shear stress and the fluctuating velocity both in the inner and in the outer boundary layer in rough-wall turbulence are increased obviously. Liang and Liu (1994)[4] showed that the burst frequency increases with the roughness Reynolds number in their experimental study conducted in a rectangular flume with the roughness Reynolds number from 0.04 to 73. Mao et al. (2002) [5] studied the burst patterns and the characteristics of near-wall turbulence in different conditions of

[1] Corresponding author: School of Aerospace, Tsinghua University, Beijing China, Fax. +8610-62794628, E-mail: zhanghq@tsinghua.edu.cn.

surface roughness. It was found that with the increase of roughness Reynolds number, both the burst scales and the sweep scales increase and the non-dimensional burst cycle significantly increases. Yang, Zhang and Wang(2008)[6] analyzed the effects of different roughness surface on coherent structures in near wall turbulence using large-eddy simulation (LES) method with a fictitious roughness element model. They found that the mean Reynolds stress, the r.m,s velocity, the streak spacing and the average diameter of near wall quasi-streamwise vortices in the rough-wall flow are larger than those in the smooth wall flow. In addition, the increasing trend is more prominent when the roughness element is higher. Summarized the above documents, it is shown that the coherent structures of inner boundary layer in rough wall turbulence have many significant changes, such as the increase of the streak number, the decrease of the streak spacing, and the shortening of the burst cycle, compared with those in the flow with a smooth wall.

For a careful understanding of the effects of roughness on the near-wall coherent structures, a row of roughness elements is placed on the bottom wall in a flume circulation system and the flow fields are recorded by means of high-speed video camera utilizing the hydrogen bubble flow visualization technology in the present experiments. The variations of coherent structures are then analyzed in different wall conditions when the Reynolds number is changed from14299 to48000.

2 EXPERIMENTAL SYSTEMS

The flume circulation system employed in the experiment is shown in Figure 1. The water is pumped and driven by a DC-motor. Before the water flow through the test section, it is rectified. The test section is 0.2m × 0.15m × 1.3m. The averaged velocity of test section is 0-0.8m/s. The mean background turbulence intensity at the entrance of the test section is less than 2%.

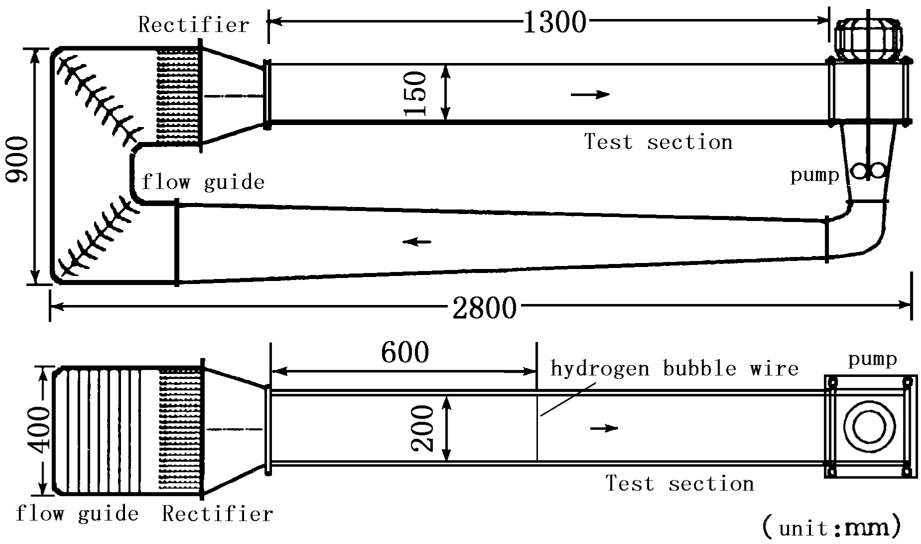


Fig. 1. Experimental flume schematic

The fine tracer bubble is generated by a lab-made hydrogen bubble generator. The high-purity platinum wire used as the cathode is 0.1mm in diameter. The distance from the Pt wire to the bottom wall is less than 1mm. The input pulse voltage in the electrode can be adjusted from 5 to 110V and the frequency from 1 to 1000Hz according to the experimental condition.

The recorded test section is illuminated by a semi-conductor solid laser with a adjusted power from 0 to 2.5W. The width of the light sheet is controlled less than 0.5mm in the test region. A Sony Digital video camera is used to record the flow field. The stereoscopic photographic system is shown in Fig. 2. The laser moves in the plane XOY.

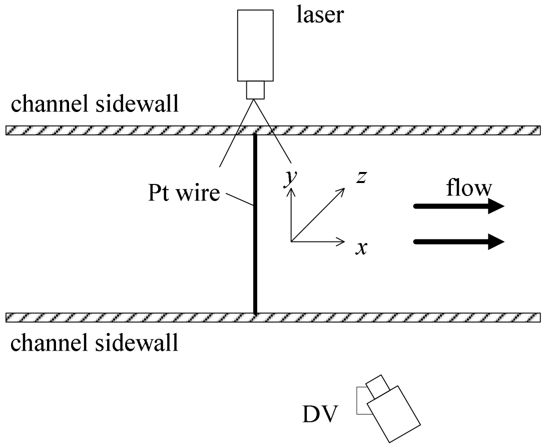


Fig. 2. Stereoscopic photographic system

3 EXPERIMENTAL CONDITIONS

The smooth small spheres are taken as the roughness elements, whose diameter are 6mm, 5mm, 4mm and 2.3mm [7]. The roughness elements are fixed at a distance of 6cm upstream from the platinum wire. They are evenly arranged in a row with the 2cm spacing each other. Taking the roughness element in diameter of 6mm as an example, the placement is shown in Fig, 3.

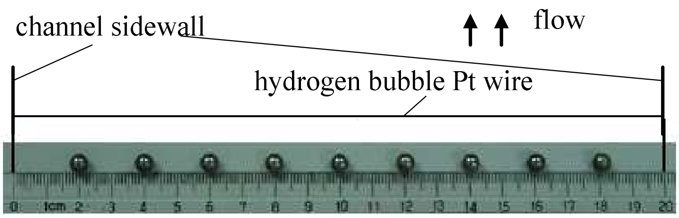


Fig.3. Roughness elements in diameter of 6mm

The flow Reynolds number is defined as in the present study,

$$\mathrm{Re} = \frac{V \cdot d_H}{v}$$

where V is the flow velocity; v is the water kinematic viscosity coefficient, $v = 1.007 \times 10^{-6}$ m^2/s and d_H is the hydraulic diameter,

$$d_H = \frac{4A}{S}$$

where A is the cross-section area of channel flow and S is the wetted perimeter. The experiment conditions are listed in Table 1.

The camera positions in the experiments are shown in Table 2. The angles in Tab. 2 are specified between the camera and the flow direction.

Table 1 Experimental conditions

Wall conditions	Flow velocity m/s	Reynolds number
Smooth wall Roughness diameter is 2.3mm Roughness diameter is 4mm Roughness diameter is 5mm Roughness diameter is 6mm	0.06	14299
	0.08	19066
	0.11	26216
	0.13	31200
	0.15	36000
	0.18	43200
	0.2	48000

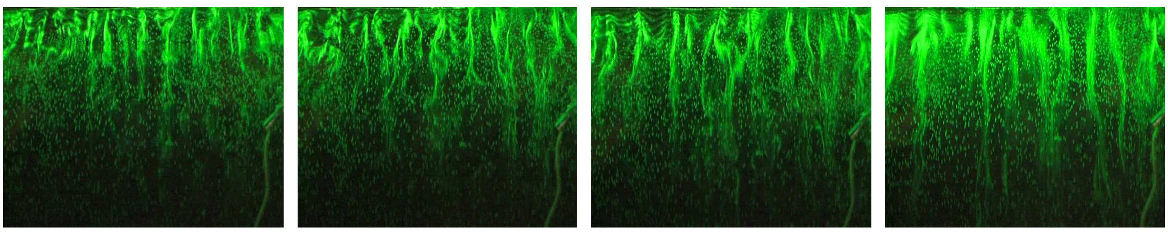
Table 2 Camera position

camera position	high angle shot	Side shot (Linear light source is 1cm from the platinum wire)	Side shot (Linear light source is 3 cm from the platinum wire)	Side shot (Linear light source is 6 cm from the platinum wire)
Focal length m	1.1	1.1	1	1
Angle °	51	35	31	34

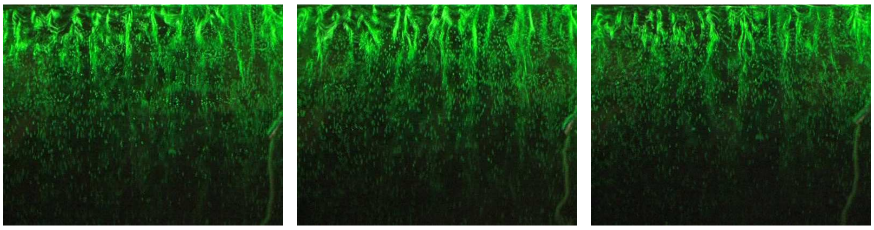
4 THE EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Characteristics of coherent structures in the smooth wall turbulence

The camera is used at the high angle shot position, and the characteristics of streaks in the smooth wall turbulence are shown in Fig. 4.



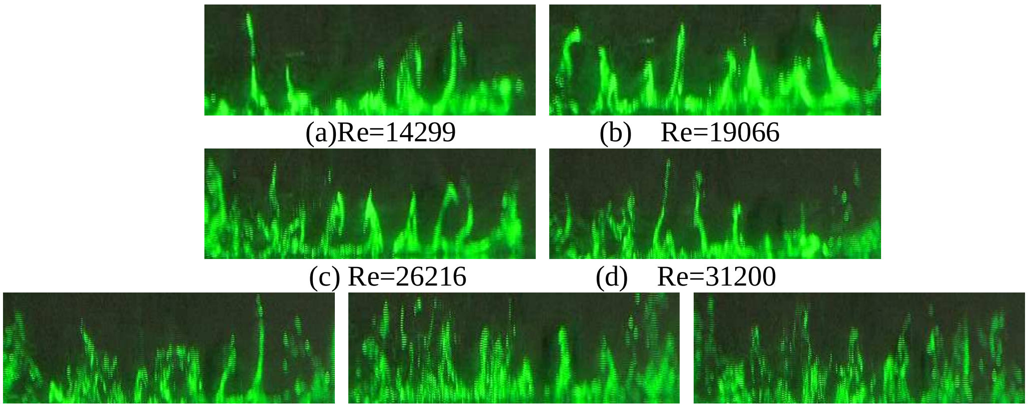
(a)Re=14299 (b)Re=19066 (c)Re=26216 (d) Re=31200



(e) Re=36000 (f) Re=43200 (g) Re=48000

Fig.4. Characteristics of streak in smooth surface turbulence in different Reynolds number

The characteristics of vortex in the smooth wall turbulence are shown in Fig. 5, when the camera is placed at the position of Side shot and there the linear light source illuminates the cross-section with a 6 cm distance from the platinum wire.



(a)Re=14299 (b) Re=19066
(c) Re=26216 (d) Re=31200
(e) Re=36000 (f) Re=43200 (g) Re=48000

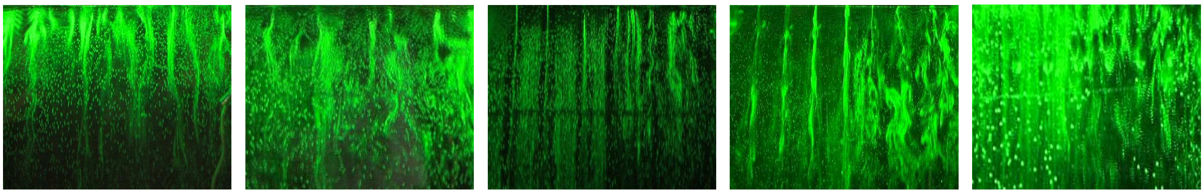
Fig.5. Characteristics of vortex in smooth surface turbulence in different Reynolds number

The pulse electrode intermittently releases the hydrogen bubbles. The bubbles form the streaks in the low-speed zones, which is shown in Fig. 4. The streaks are randomly generated, but the statistical streak number is identified. It is observed that the streak length shortens, the streak number increases and the streak spacing decreases in the smooth wall turbulence as the Reynolds number. The vortices of coherent structure are clearly seen from Fig.5. The vortex height and vortex number also increase with the Reynolds number.

4.2 Characteristics of coherent structures in wall turbulence with roughness elements

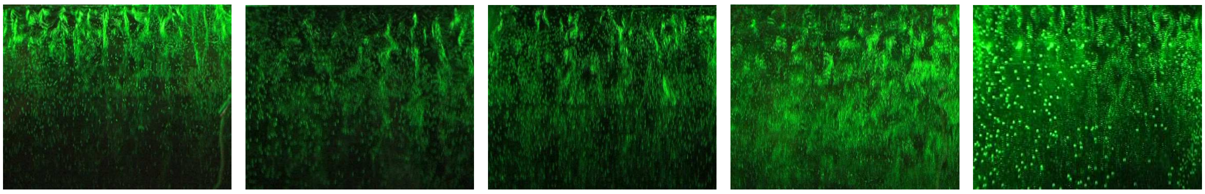
The longitudinal streak structures for the smooth and roughness wall turbulence are compared in Fig.6 when the Reynolds number is14299. The same comparisons are shown in Fig. 7 when Reis equal to43200. Here d is the diameter of roughness elements

It is shown that the median roughness elements, as shown in Fig. 7 (c)-(d), bring the disturbance and behind them there are vortex streets. The vortex streets are then the dominated structures in the near wall turbulence. Both the numbers and the positions of streaks are related to the roughness element positions. However, even with the smaller and very large roughness element on the bottom wall, the streaks number and positions are still very random generated and they do not dominated by the roughness elements.



(a) smooth wall (b) d=2.3mm (c) d=4mm (d) d=5mm (e) d=6mm

Fig.6. Comparisons of streak structures for the smooth and roughness wall turbulence at Reynolds number is 14299



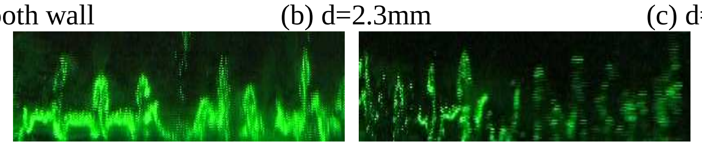
(a) smooth wall (b) d=2.3mm (c) d=4mm (d) d=5mm (e) d=6mm

Fig.7. Comparisons of streak structures for the smooth and roughness wall turbulence at Reynolds number is 43200

The streak structures in the transverse cross-section for the smooth and roughness wall turbulence are compared in Fig.8 when the Reynolds number is 14299 and the linear light source is in a distance of 3cm from the platinum wire. The same comparisons are shown in Fig. 9 when Reis equal to43200.

As the velocity of the channel flow increases until 0.18m/s, the near wall streaks are randomly generated, not dominated by the roughness elements arranged upstream.

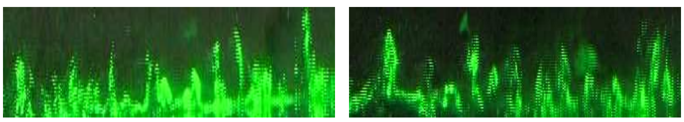
(a) smooth wall (b) d=2.3mm (c) d=4mm



(d) d=5mm (e) d=6mm

Fig.8. Comparisons of streak structures for the smooth and roughness wall turbulence at Reynolds number is 14299 in the transverse section

When Re=43200and linear light source is 3 cm from the platinum wire ,vortex structures in smooth wall and the walls which are arranged a row of roughness elements before the hydrogen bubble wire as show in figure 10 .



(a) smooth wall (b) d=2.3mm

(c) d=4mm (d) d=5mm

Fig.9. Comparisons of streak structures for the smooth and roughness wall turbulence at Reynolds number is 43200 in the transverse section

4.3 Comparisons of statistics of coherent structures

The statistical characteristics of coherent structures such as the streak number, the vortex number and the vortex height for the smooth and roughness wall are compared in Table 3, 4 and 5. Here *d* is the diameter of roughness elements.

Table 3 Statistics of streak number in near-wall turbulence

Re	14299	19066	26216	31200	36000	43200	48000
Smooth wall	11	13	14	16	17	18	19
d=2.3mm	14	15	16	18	19	21	22
d=4mm	10	12	13	15	17	17	19
d=5mm	8	10	11	13	14	16	17
d=6mm	12	14	15	17	18	20	22

Table 4 Statistics of vortex number in near-wall turbulence

Re	14299	19066	26216	31200	36000	43200	48000
Smooth wall	11	13	14	15	16	18	19
d=2.3mm	14	16	17	18	18	21	22
d=4mm	10	11	13	15	16	17	19
d=5mm	8	10	11	13	15	16	16
d=6mm	11	\	\	\	\	\	\

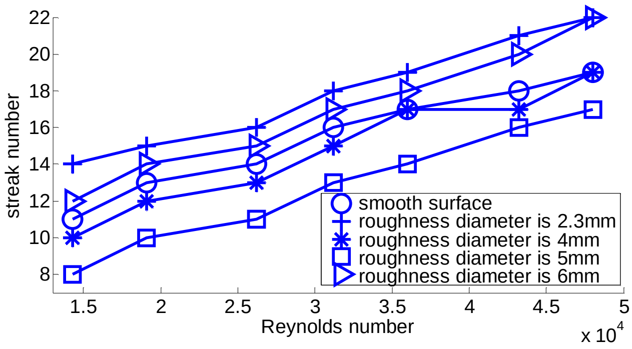
Note: '\' is the missing data in the table.

Table 5 Statistics of vortex height in near-wall turbulence

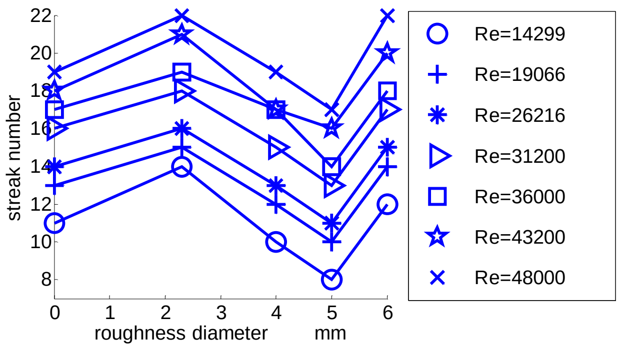
Re	14299	19066	26216	31200	36000	43200	48000
Smooth wall	8.5	10	11	14	15	16	18
d=2.3mm	8	10	12.5	14.5	16	18	20
d=4mm	8	9	10.5	12	13.5	15	16.5
d=5mm	8	8.5	10	11	13.5	14.5	16
d=6mm	9	\	\	\	\	\	\

Note: '\' is the missing data in the table.

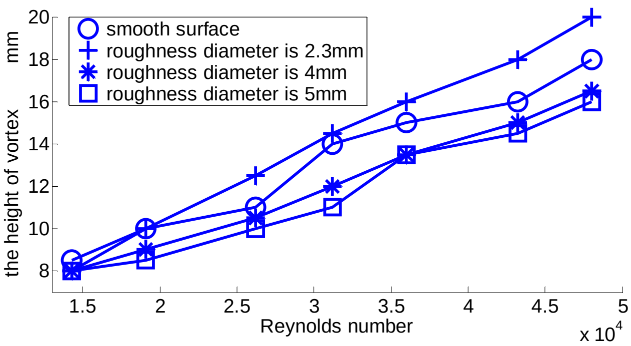
The statistical data are also plotted in Fig.10. It is shown that both the streak number and the vortex height for the smooth and roughness wall turbulence increase with the Reynolds number. In the same Reynolds number condition, the streak number and the vortex height first increase, then decrease and increase again as the diameter of roughness elements increases.



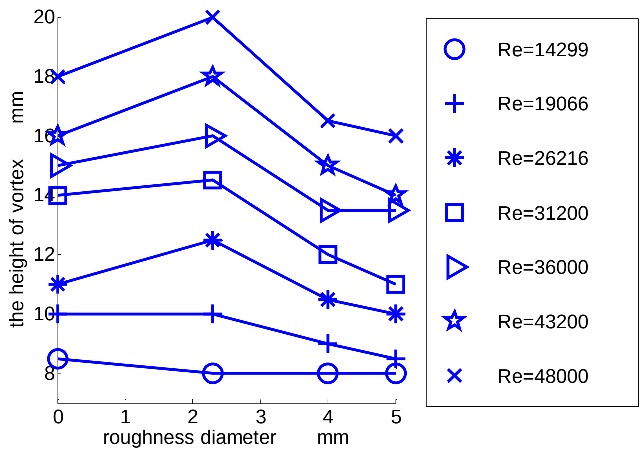
(a)Streak number for different velocity



(b) Streak number for different roughness elements



(c) Vortex height for different Reynolds number.



(d) Vortex height for different roughness elements

Fig.10. Comparisons of statistics of turbulent structures

5 CONCLUSIONS

The effects of the arranged roughness elements row on the near-wall coherent structures are investigated in a channel flow by using flow visualization.

(1) The streak number, the vortex number and the vortex height increase with the Reynolds number for both smooth- and roughness-wall cases.
(2) For the cases with the same Reynolds number, the streak number and vortex height increase firstly, then decrease and increase again with roughness-element size.

ACKNOWLEDGMENTS

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