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Experimental Study of Particle Motions in a Rough Plate Boundary Layer

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Abstract

In this paper, the motions of particles in a rough plate boundary layer are studied in a wind tunnel. The particles with the diameter range of 40μm to 140μm are made of polystyrene. In the present experimental wind velocity, the corresponding Strokes numbers (the ratio of the particle relaxation time to the fluid characteristic time, written as Sn in this paper) are from 16 to 190. The rough elements are made of an abrasive paper on which different spherical particles cover. Three average diameters of those spherical particles are 51μm, 61μm, and120μm, respectively. The particle velocity is measured using PTV (Particle Tracking Velocimetry) function embedded in a LaVision 2D PIV (Particle Image Velocimetry) system. The particle trajectories are recorded using a Phantom v9.1 HSC (high speed video camera) with time-lapsed exposure shooting method. The study is focused on the particles within the logarithmic law layer ($30<y^+<360$ for the present experiments) and on the surface of the plate ($y^+\approx 0$). Following results can be given: 1) Four-way coupling interaction occurs between particles, flow and surface of the plate. Herein, four-way coupling means interaction like flow to particles, particles to particles and the opposite effects between these two objects. The rich phenomena of the particles, such as deposition, rolling, bounce, fluctuation and collision occur in the flow or on the surface of the plate; 2) Both of the Stokes number and rough element size take effect on the particle dynamics and distribution. As the Stokes number increased for any surface, particle distribution density increased for $30<y^+<200$. As the rough element size increases, most of particles move to the wall. Most of particles appear in the area of $30<y^+<180$ for the rough element size 51μm. Most of particles appear in the area of $30<y^+<100$ even below for the rough element size 61μm and 120μm. 3) Particle deposition on the surface is also affected by both the Stokes number and the rough element size. The ratio of deposition decreases with the increased the Stokes number of particles.

1 Introduction

Movement of particles in the plate boundary layer especially with a rough surface is an attracting issue. Deposition, collision, and suspension affairs may present in such boundary layer flow. Herein, particle deposition on the surface of an object is often both of expected and unexpected, e.g., protecting dust from the surface of a heat transmitter to keep power [1]; adsorption of particles may also purify air [5].

In a turbulent plate boundary layer, the two-way coupling interaction exist in particles and particles, particles and flow. Meanwhile, interactions between flow and particles are widely concerned [7]. Coherent turbulence structures (strikes, hairpin vortex etc.), turbulent affairs (sweep, injection, burst), Reynolds stress and so on, may change particle dynamics including rotation, collision, vice versa [8]. Through PIV, PTV measurement, particle and flow can be investigated to discover the physics of such kind of the interaction **[**4, 9**]**. Where the particles are going finally is the most concerned question in engineering. Above issues will become more interesting when the rough element is introduced to the surface of the plate. Firstly, the rough element may modify the flow on the plate boundary layer and change two-way coupling between particle and flow. It may be four-way coupling [2]. Secondly, changing the size of the rough element, one may control particle deposition since the rough element may change flow structures in the boundary layer [3]. Thirdly, the rough elements may change the particle kinematics after particles impacting on the surface [6].

Under above consideration, we investigate how the particles interact in a turbulent boundary layer with a rough element surface.

2 Experimental details

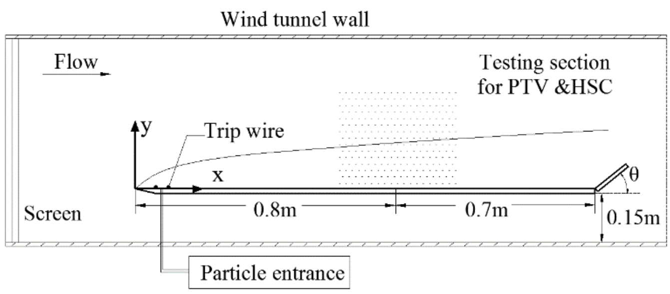

Figure 1 Experimental setup

The experiments were carried out in an open-looped wind tunnel with a working section of 0.5 m × 0.5 m × 2.4 m. The experimental setup is shown in Fig.1. Three damping screens were installed at the entrance of the working section to keep the incoming flow to be more stable at lower wind speed. An aluminium alloy plate with 1.5m long and an end plate (to be used to adjust pressure gradient along the plate) was horizontally mounted in the wind tunnel. The plate is at 0.15m over the bottom wall of the wind tunnel. Two tripping wires were fixed at the front of the plate (left in Fig.1). The particles were introduced between the two tripping wires through a slender pipe. The wind velocity is fixed at 4.3 m/s for all measurements. The flow visualization and PTV test were conducted in the shadow area (0.06m×0.03m) in the Fig.1. The centre of the shadow area is fixed at 0.8m from the leading edge of the plate. To study the rough elements effect on the interaction between particles and the boundary layer flow, a series of abrasive paper with the analogy rough element sizes of 51μm, 61μm and 120μm, respectively, through the spherical particles were coated on the surface. In the case of smooth plate, the boundary layer parameters are listed in Table 1. The particles parameters are shown in Table 2.

Table 1 flow parameters of the plate boundary layer

name	symbol	value	unit
Flow velocity	U	4.3	m/s
Boundary layer thickness	δ	0.039	m
Reynolds number based on x	$Re_{x=0.8}$	2.3×10^5	-
Reynolds number based on the momentum thickness	Re_θ	1100	-
Wall shear stress	τ_w	0.055	Pa
Wall friction velocity	u_τ	0.214	m/s
Kolmogorov	τ_g	3.23×10^{-4}	s
y^+	$y\,u_\tau/\upsilon$		
x^+	$x\,u_\tau/\upsilon$		

The velocity profile at x = 0.8 m was measured by a boundary layer hot-wire sensor. The boundary layer thickness δ obtained from the velocity profile is about 0.039m as shown in Table 1. The particles distribution at instant and particle trajectories are measured using a Phantom v9.1 high speed digital camera. To show the clear particle trajectory, time-lapsed exposure shooting method was used. The velocities of particles were measured using PTV technique embedded in a LaVision 2D PIV.

Table 2 particle parameters

diameter (μm)	density (g/cm³)	relaxation time (s)	Stokes number
40	1.05	5.2×10^{-3}	16
60	1.05	1.2×10^{-2}	36
100	1.05	3.3×10^{-2}	100
140	1.05	6.3×10^{-2}	190

To study the particles deposition, the ratio of deposition is defined by

$$\eta = \frac{m_1}{m_2}\times100\% \qquad (1)$$

where m_1 is the mass of the deposited particles, m_2 is the total mass of the particles entries the flow.

3 Results

3.1 Rough element size Effect on Particles Kinematics for 30<y+<360

Figure 2 shows the distribution of the particles over the plate. Most of particles are concentrated for $30<y^+<360$. For the case of the smooth surface of plate, particles distribution is more even and particles are concentrated near by the plate. The particles with the Stokes number 16 are well-distributed as shown as Fig.2 (a). Particles with the larger Stokes number (say, 100) are apt to concentrate to the plate surface as shown as Fig 2(e). For the case of the rough surface, the particles distribution is uneven. As the rough element size increases, the particles move to the wall and concentrate near by the wall. Most of particles present in the area of $30<y^+<180$ for the rough element size 51μm. Most of particles present in the area of $30<y^+<100$ even below for the rough element size 61μm and 120μm. The increased rough element size give rise to an increased effect on the boundary flow, such as friction drag increases, momentum decreases near by the wall. Accordingly, the deposition of the particles are enhanced.

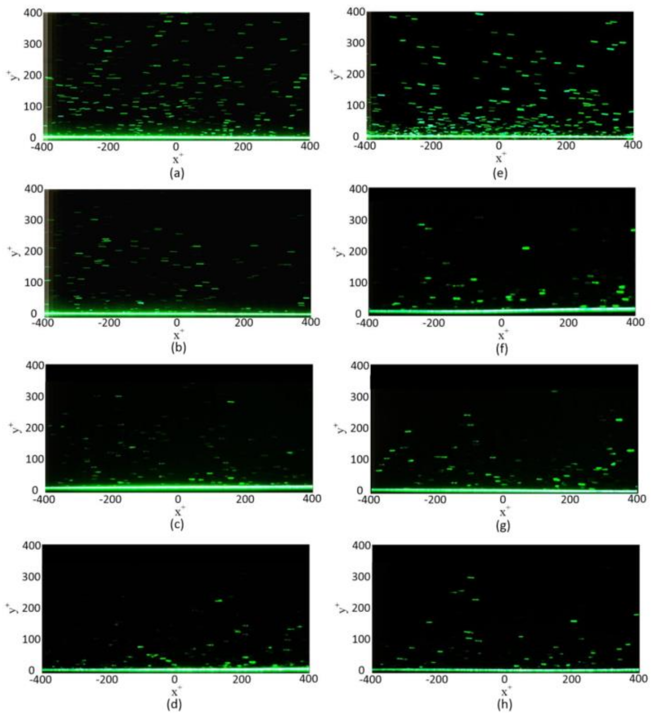

Figure 2 instantaneous distributions of particles in the boundary layer. From the top to the bottom, the rough element size of each row is 0 μm, 51μm, 61μm and 120 μm, respectively. The left column is for the particles with the Stokes number of 16, the right one for that of 100.

To further present the distribution of the particles with or without effect of the rough element, the statistic particles concentration density normal to the plate is given in Fig.3.

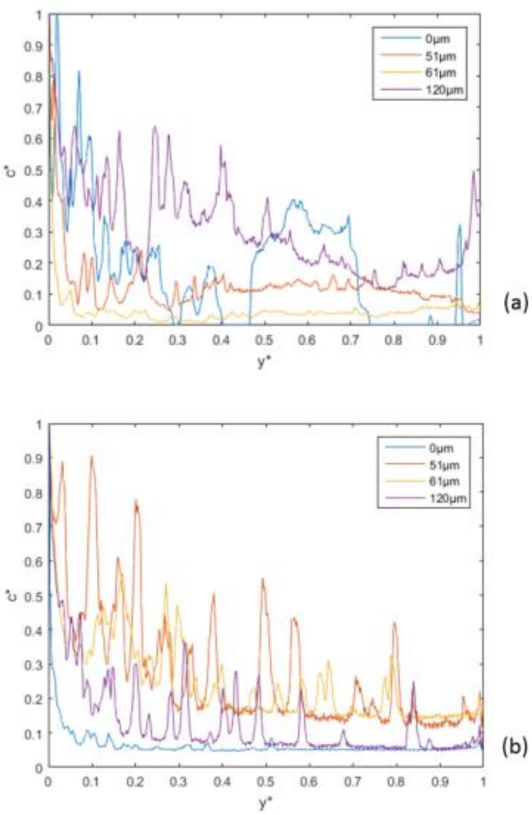

Figure 3 statistic particles concentration distribution along y*. (a) Sn = 16; b) Sn = 100.

The c* presents the ratio of the number of the particles in the unit area at y* and the total number of the particles concentrated on the surface in the Figure 3, where dimensionless height y* is normalized using boundary layer thickness. The blue line represents the case of the smooth plate. For the smooth plate, particles with the smaller Stokes number 16, the c* presents quite fluctuation as y* increases. On the contrary, particles with the lager Stokes number 100 present a stable c*, most of particles concentrated to the wall. Fig.3a shows the case of the Stokes number is 16. For the rough element size is 51μm, c* increases as y* increases; for the rough element size is 61μm, c* almost keep a constant as y* increases; for the rough element size is 120μm, c* decrease as y* increases. Fig. 3b shows the case of the Stokes number is 100. All the c* present a fluctuation change as y* increases.

Figure 4 presents the typical trajectories for different particles. Particles present abundant moving trajectories. For small Stokes number 16 and the smooth plate, particles mainly move along the flow for $y^+> 30$. A few of particles for $y^+<30$ may impact on the wall and fewer particles bounce off the wall (Fig 4a). For larger Stokes number 100, particles behave more active. For $y^+> 200$, most of particles move along the flow direction. For $y^+< 200$,

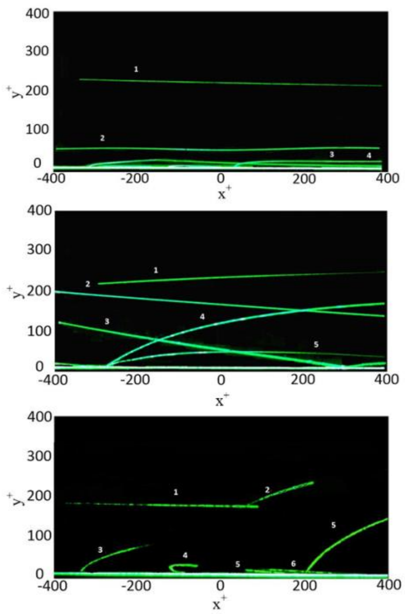

Figure 4 The typical particle trajectories. (a) Stokes number is 16, smooth plate; (b) Stokes number is 100, smooth plate; (c) Stokes number is 100, rough element size is 61μm.

some particles move down to the wall and may rebound from the wall and then drop on the wall again, some particles may stay on the wall. Some particles may rebound off the boundary layer and move into the out flow as shown as the line 4 in Fig.4b. On the rough plate, particles collide the wall more frequently than that on smooth plate. Most of particles stay in the rough plate but quite few particles may rebound off and return to the flow (Fig 4c).

The instantaneous velocity distributions of the particles obtained from the PTV measurement are given in Fig. 5. Two silver lines give the boundary of $30<y^+<360$. For Stokes number is 16 and the smooth plate, almost a half of the particles with higher velocity (>3.75 m/s) are distribute evenly at $30<y^+<360$. Particles with lower velocity (< 2.75 m/s) mainly occur at the region nearby the wall. Particles with higher velocity distribute the top of the area $30<y^+<360$, and particles with lower velocity distribute the bottom of the area $30<y^+<360$. For the Stokes number is 190, the situation is different. Whatever on the smooth plate or rough plate, most of particles with lower velocity are distribute nearby the wall. As Stokes number and rough element size increase, the angle between particle velocity and flow increase.

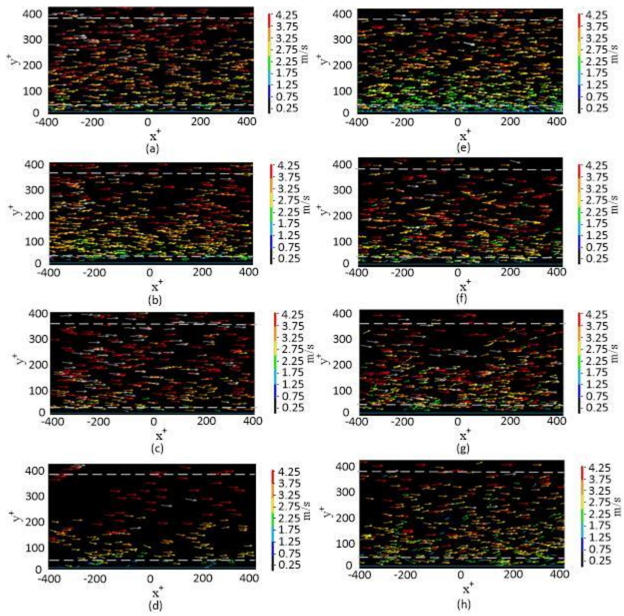

Figure 5 instantaneous velocity distributions of the particles based on the PTV measurements in the boundary layer. From the top to the bottom, the rough element size of each row is 0 μm, 51μm, 61μm and 120 μm, respectively. The left column is for the particles with Sn = 16, the right one for Sn = 190.

3.2 rough element size effect on particles deposition

Some particles will stay on the plate wall in the present studying window (0.06m×0.03m). The ratio of deposition mass (η, is defined in section 2) is measured and given in Fig. 6. The Stokes numbers of the particles are 16, 36 and 100, respectively. The black line presents the deposition ratio of particle with Stokes number 16. For all the tested rough element sizes, η for Sn=16 is the largest value. The second is for Sn = 36. The smallest one is for Sn = 100.Compared with the smooth plate, the rough element size of 51μm increases the deposition ratio. At 61μm, η still a little bit increases for Sn = 16, but decreases for Sn =36. At 120 μm, all η values are less than that at 51μm.

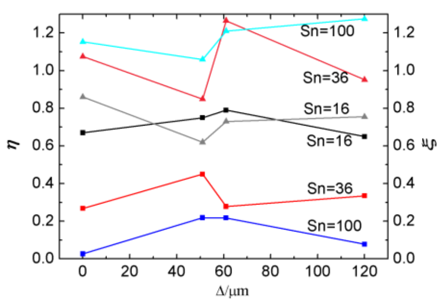

Figure 6 the deposition ratio versus the rough element size and Stokes number, and the ratio of the number of resuspension and that of on the wall

Figure 6 also shows another ratio between the number of re-suspension and the number of wall-touched, marked by ξ. The statistics analysis is applied to calculate the ratio. The number of particles bounced off the wall is counted. On the smooth plate all kinds of particles can rebound and return to the flow. Fig. 6 shows that larger particles have stronger ability of bounce. However, on the rough plate, the rough element size gives an effect on the ratio of ξ. At 51μm, ξ reaches the minimum value for all kinds of particles. At 61μm the ratio of ξ reaches the top. At 120μm, the ξ of particles with the Stokes number of 36 drops. Other kinds of particles remain the top. Figure 7 gives a common picture formed by particles on the plate. The pattern is much like the sand waves in the desert.

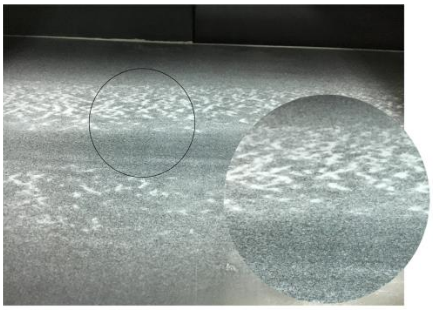

Figure 7 the pattern on the plate (Sn = 100, smooth plate)

4 Conclusion

In this paper, the preliminary study of the rough element effect on the particle kinematics was carried out. The study is focused on the particles in the logarithmic law layer ($30<y^+<360$ for the present experiments) and on the surface of the plate. The following conclusion can be drawn: 1) four-way coupling interaction occurs between particles, flow and surface of the plate. The rich phenomena of the particles, such as deposition, rolling, bounce, fluctuation and collision, occur in the flow or on the surface of the plate; 2) both of the Stokes number and rough element size influence on the particle dynamics and distribution. As the Stokes number increased for any surface, particle distribution density increased for $30<y^+<200$. As the rough element size increases, the particles move to the wall. Most of particles present in the area of $30<y^+<180$ for the rough element size 51μm. Most of particles present in the area of $30<y^+<100$ even below for the rough element size 61μm and 120μm. 3) particle deposition on the surface is also affected by both the Stokes number and the rough element size. When the rough element size drops in between 51μm to 61μm, the deposition reaches a peak.

Acknowledgement

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