17th Australasian Fluid Mechanics Conference
Auckland, New Zealand
5-9 December 2010

LDV Measurements of a Turbulent Channel Flow with Smooth and Rough Surfaces

Y. B. Zhang and D.F. Che

State Key Laboratory of Multiphase Flow in Power Engineering
Xi'an Jiaotong University, Xi'an 710049, China

Abstract

Detailed Laser-Doppler Velocimeter (LDV) measurements have been carried out in a turbulent rectangular channel flow with smooth and rough surfaces at different Reynolds numbers. The measured distributions of turbulence statistics across the half channel height at different wall conditions, including mean velocity, turbulence intensity, skewness factor, flatness factor and Reynolds shear stress are all reported and compared. The turbulent statistical quantities on different surfaces exhibit significant differences in both the inner and the outer region, which suggests that the roughness element has an important role on turbulent flow structure extending into the whole layer. There is a significant increase in the streamwise turbulence intensity and a slight increase in the normal turbulence intensity and the Reynolds shear stress over the rough surface. The profiles of the streamwise skewness factor become flatter over the rough walls, while the flatness factor distributions are nearly the same for different surfaces.

Introduction

Rough surfaces are common in various engineering applications such as pipe systems, turbine blades, heat exchangers, aircraft and ship hulls, and their effects on turbulent flow cannot be neglected. In many cases, the surface conditions degrade over time from hydraulically smooth to rough. A typical example is the pipe or channel flows involved with corrosion and erosion. While corrosion attack is progressing, corrosion product with rough morphology precipitates on the smooth steel surface. Flow enhanced corrosion mechanism is strongly dependent on the properties and breakdown of surface films [10, 15]. Although many investigations has pointed out that turbulent flow may exert larger forces on steel surface and corrosion film than that in stationary solutions and may result in film fracture and serious localized corrosion, the fact that wall roughness due to corrosion also inversely impacts the flow structure near the film is scarcely realized. It is an urgent issue to study the turbulent flow on rough corrosion film surfaces and clarify the interactions between the flow and roughness.

In this paper, the measurements of turbulence statistics in a channel flow with smooth and artificial rough surfaces at different Reynolds numbers have been carried out by a three-dimensional Laser-Doppler Velocimeter (LDV) system. The roughness elements are transverse V-shaped grooves with 120 degree vertex angle. Distributions of the mean velocities, turbulence intensities, high-order moments and Reynolds shear stress on smooth and rough surfaces are all presented and compared to examine the influences of roughness on them.

Experimental

Flow Loop and Test Section

To obtain detailed and reliable turbulence statistics measurements, a small-scale flow loop has been designed and built. The working fluid is pumped from water tank, flows through rotameter, stabilizing cavity and a flow-developing section with length of 1.2m, and enters into the test section of rectangular channel. The stabilizing cavity with regularly cubic configuration and with inclusions of a distributing pipe, a honeycomb and a contraction section is able to implement functions of stabilizing, rectifying and accelerating uniformly inflow. In order to alleviate the effect of pump vibration on the test section, the water tank and pump are fixed on an individual shelf separated with the test section, and the connection between the two shelves is flexible.

The dimensions of the test section, a rectangular channel, are 20mm high, 100mm wide and 1060mm long. The bottom surface of the channel can be removable to change the wall condition. The rough surfaces are fabricated by engraving V-shape grooves on the original smooth Plexiglas plates. The properties of the grooves are shown in figure 1, with characteristic parameters including depth (***e***), angle (***α***), pitch (***p***) and width (***w***). Two rough plates are investigated in the present experiment and the rough element is transverse 120° V-shape groove with 0.8mm deep. The two plates are composed of 213 grooves with the spacing equalling to 5 times depth of the groove and 133 grooves with the spacing equalling to 8 times depth of the groove respectively. In the following sections, the former rough surface is called 1# plate and the latter 2# plate.

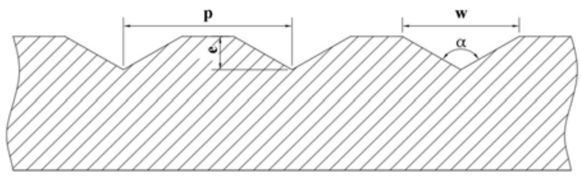

Figure 1. Schematic drawing of the roughness element (side view).

Measurement Technology

A copper–constantan thermocouple with the maximum temperature deviation of 0.2℃ is used to measure the water temperature. The pressure drop over the test section is measured by a high-resolution micro differential pressure transmitter with an accuracy of 0.1%. Meanwhile, the turbulence statistics measurements are implemented using a TSI 9253-type three-dimensional LDV system operating in backscatter mode. The measuring control volume is about 85μm in diameter and 800μm in length and is positioned at the central axis of the channel in the spanwise direction. Position of the measurement volume is controlled by a three-axis traverse table with 0.01mm resolution. Typically, 10000 data points are acquired at each measurement location to compute the mean velocity and turbulence quantities. Velocity bias resulted from random arrival of particles can be corrected by weighting the velocity component values by the time they reside in the measurement volume. A type of hollow glass particles is adopted as the tracer.

Experimental Conditions

The region chosen for the measurements lies 1875cm downstream from the outlet of the contraction. This length, about 90 times channel height, is considered to be sufficient to ensure a fully developed turbulent channel flow, and is far enough away from the channel outlet to ensure no outlet disturbances to the flow. Measurements are carried out at two different Reynolds numbers, namely 7200 and 17400, which are based on the half channel height, centreline velocity and fluid kinematic viscosity.

The velocity field is measured from the bottom wall to the channel center along the centreline in the spanwise direction. The measuring positions of rough surfaces are chosen at two different locations in the streamwise direction. One is just above the valley of the groove and the other lies the middle of the plateau between the consecutive grooves.

Estimation of Friction Velocity and Virtual Origin

In the experimental study of wall bounded turbulent flows, the determination of the friction velocity and virtual origin is critical, which becomes more crucial for flows on rough wall. The wall shear stress can be determined by direct measurement or indirect approaches such as wall similarity techniques. For rough surfaces, direct measurement of wall shear stress is a tough task. Instead, the Clauser method [5], one of the most famous wall similarity techniques, is often adopted to estimate the friction velocity and virtual origin, although it has been pointed out that this method may result in more than one combination of friction velocity, virtual origin and roughness function to satisfy the logarithmic law. Perry and Joubert [8] argued that if the wall shear stress or friction velocity is known by some other method, the Clauser method affords a fairly accurate means of determining the two other variables. In this paper, the friction velocity of flow on the rough surfaces is calculated from the pressure drop measurements. Then the virtual origin and roughness function are simultaneously derived by another wall similarity technique, i.e. the Spalding full velocity profile method [11], to avoid the subjective selection of log-law region range encountered in the Clauser method.

Result and Discussion

Mean velocity profiles

The measured streamwise mean velocities on the smooth and rough walls, normalized by inner wall variables, are shown in figure 2. The solid line represents the Spalding model with κ=0.38 and B=5.5. For the smooth surfaces, the measured velocity profiles at different Reynolds numbers collapse into a single curve and follow the Spalding model very well in the inner and over-lap regions. All the profiles on the rough surfaces shift downward by different amount, which is usually termed roughness function. The roughness function is a measure of the increase in drag due to roughness and is dependent on rough surface characteristics and Reynolds number.

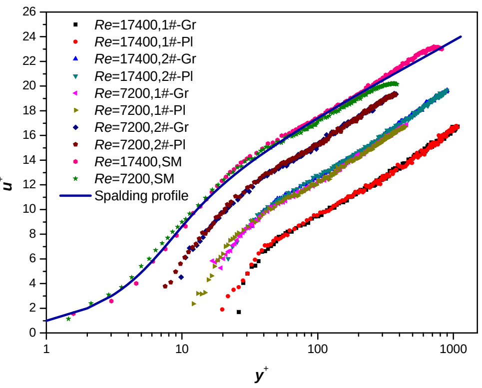

Figure 2. Streamwise mean velocity distributions normalized by inner variables for different rough surfaces.

In the present cases measured, the roughness function approximately equals to 7.72 for 1# plate at ***Re***=17400, 4.8 for 1# plate at ***Re***=7200, 4.43 for 2# plate at ***Re***=17400, 1.78 for 2# plate at ***Re***=7200, respectively. At the same Reynolds number, more dense rough elements result in larger value of the roughness function, which shows that the amount of the groove (or the spacing) is one important parameter for evaluating the effects of roughness. Furthermore, although there are very small differences between the roughness functions above the grooves and those above the plateau between the grooves, it is found that the former is generally slightly higher than the latter in the process of calculating the roughness function using the method mentioned in the previous section. This phenomenon shows that the drag is evolutive in the streamwise direction, which is also pointed out by Wahidi et al. [13].

Turbulence intensities

Figure 3 gives the root mean square (rms) of streamwise velocity fluctuation normalized with the friction velocity at different Reynolds numbers. The present measurements on the smooth wall show great agreement with the DNS result [1]. Compared with those on the smooth wall, the streamwise turbulence intensity profiles on the two rough surfaces become more flat. The peaks are significantly attenuated by the presence of roughness. The increase of Reynolds number and the decrease of the pitch of grooves may both reduce the peaks of turbulence intensity. The lower turbulence intensity in the near wall region may be attributed to the weakening of the streamwise vortices because of the grooves. The attenuation of maximum turbulence intensity has also been reported by Bakken et al. [2], Ching [4] and Wahidi et al. [13].

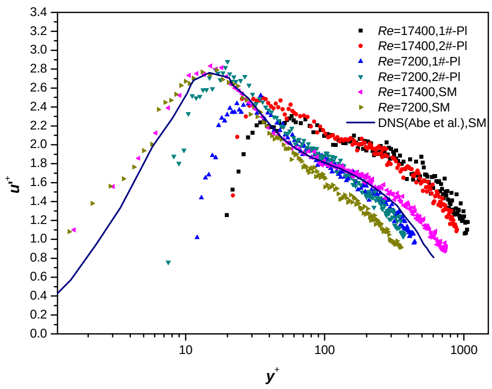

Figure 3. Streamwise turbulence intensity distributions normalized by inner variables for different rough surfaces. Symbols are for present experiments; Solid line for DNS of Abe et al. [1].

Figure 4 includes the profiles of streamwise and wall-normal turbulence intensities expressed against the outer variables. The classical viewpoint of wall similarity hypothesis [12] states that outside the roughness sublayer, the distributions of turbulence intensities normalized with wall variables should be essentially the same over smooth and rough surfaces. However, the present measurements show that the turbulence intensities in the streamwise direction on the rough surfaces are apparently higher than those on the smooth wall, while all the profiles on the rough surfaces collapse into single line in the outer region. The enhancement of the turbulence intensity in the most part of the channel may be due to the effects of roughness extending well into the outer region, which is also proposed by Krogstad et al. [6]. The situation at ***Re***=7200 is similar with that at ***Re***=17400. To avoid crowding, the data at ***Re***=7200 have not been included in the figure. Different from the findings by Krogstad et al. [6], the effect of the roughness on the wall-normal turbulence intensity is weaker than that on the streamwise one in the present case. However, the differences of normal turbulence intensity on the smooth and rough surfaces are still distinguishable. It is a pity to note that the present wall-normal turbulence intensity measurement is unavailable in the inner layer because one blue beam for the normal direction cannot access into the channel in this region.

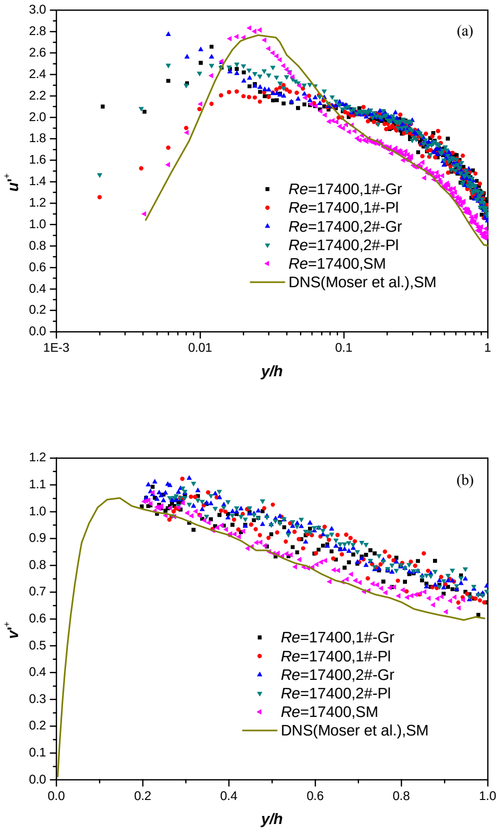

Figure 4. Turbulence intensity distributions normalized in global coordinates. (a) Streamwise; (b) Wall-normal. Symbols are for present experiments; Solid line is for DNS of Moser et al. [7].

Skewness and Flatness Factors

The skewness factor and flatness factor profiles of the streamwise velocity component are shown in figure 5. The positive values of skewness factors in the very near wall region indicate that there happen strong sweep events, while the minus ones in the outer region mean strong ejections away from the wall. The profiles on the rough surfaces are almost monotonic in the inner region, contrary to the negative peak for the smooth surface. Bakken et al. [2] attribute it to the partial break-up of the streamwise vortices. The present flatness factor distributions on the grooved walls are approximately similar to those on the smooth surface. This finding is in agreement with the measurements in rough-wall boundary layer by Bandyopadhyay and Watson [3].

Reynolds Shear Stress

Although the Reynolds shear stress data in the inner region cannot be obtained for the same reason as the normal turbulence intensity measurements, the results in the outer region are presented in figure 6 versus global coordinates. The present measurement on the smooth wall is confirmed by LDV measurements of Wei et al. [14]. The Reynolds shear stresses on the different rough surfaces are very close and slightly higher than that on the smooth wall. The same was found by Krogstad et al. [6] and Perry and Li [9]. The increased Reynolds shear stresses over the rough walls suggest that the larger-scale organized motion in the outer region may still feel the different wall characteristics and may not be universal.

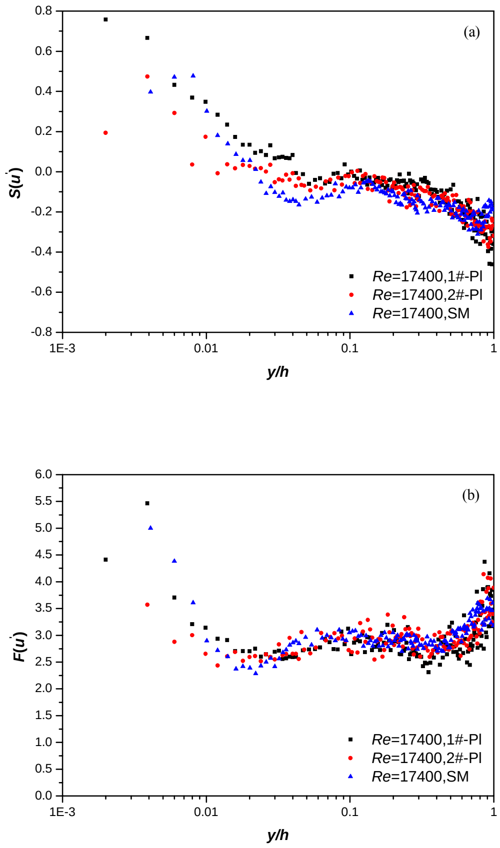

Figure 5. Higher-order moments of streamwise component over the half channel height for different rough surfaces. (a) Skewness factor and (b) Flatness factor.

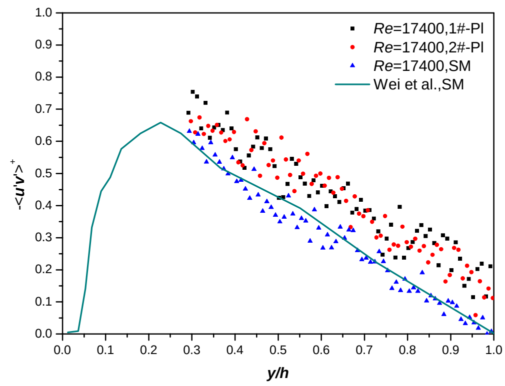

Figure 6. Reynolds shear stress distributions in the outer region for different rough surfaces. Symbols are for present experiments; Solid line is for LDV measurements of Wei et al. [14].

Conclusions

Using a three-dimensional LDV system, the turbulent flows in a rectangular channel with smooth and artificial rough surfaces formed by V-shape grooves have been investigated experimentally at different Reynolds numbers. The comparisons of the measured turbulence quantities between on the smooth and rough surfaces indicate that the wall condition has important influences on the turbulent properties and the influences are not confined in the inner region or roughness sublayer.

The effect of roughness on the mean velocity is reflected by the roughness function, which increases with increased Reynolds number and higher-density roughness element.

The turbulence intensities on the rough surfaces show significant differences from those on the smooth wall, opposing the Townsend wall similarity hypothesis [12]. In the inner region, the peaks of rms of streamwise velocity fluctuation are evidently attenuated because of the roughness. In the outer region, the presence of the grooves obviously enhances the streamwise and the wall-normal turbulence intensities, though the change of the normal turbulence intensity is weaker than the streamwise one. While the streamwise flatness factor is independent on the wall condition, the profiles of streamwise skewness factor on the rough surfaces are monotonic without a valley in the inner region. The Reynolds shear stresses on the rough surfaces are slightly higher than those on the smooth wall. All these differences indicate that the turbulent flow structure in the inner and the outer region may be both affected by the wall characteristics.

The present measurements query the classical wall similarity hypothesis, and show that the interaction between the wall and the outer region may not be negligible. The effects of different rough surfaces on the turbulent structure need to be further investigated to clarify the turbulent transport on the rough surfaces.

References

[1] Abe, H., Kawamura, H. & Matsuo, Y., Direct Numerical Simulation of a Fully Developed Turbulent Channel Flow With Respect to the Reynolds Number Dependence, Journal of Fluids Engineering, 123(6), 2001, 382-393.

[2] Bakken, O.M., Krogstad, P.A., Ashrafian, A., et al., Reynolds Number Effects in the Outer Layer of the Turbulent Flow in a Channel with Rough Walls, Physics of Fluids, 17(6), 2005, 065101-1-16.

[3] Bandyopadhyay, P.R. & Watson, R.D., Structure of Rough-wall Turbulent Boundary Layers, Physics of Fluids, 31(7), 1988, 1877-1883.

[4] Ching, C.Y., Effect of a Transverse Square Groove on a Turbulent Boundary Layer, Experimental Thermal and Fluid Science, 20(1), 1999, 1-10.

[5] Clauser, F. H., Turbulent Boundary Layers in Adverse Pressure Gradients, Journal of the Aeronautical Sciences, 21(2), 1954, 91-108.

[6] Krogstad, P.A., Antonia, R.A. & Browne, L. W., Comparison between Rough-Wall and Smooth-Wall Turbulent Boundary-Layers, Journal of Fluid Mechanics, 245, 1992, 599-617.

[7] Moser, R.D., Kim, J. & Mansour, N.N., Direct Numerical Simulation of Turbulent Channel Flow up to Re_τ = 590, Physics of Fluids, 11(4), 1999, 943-945.

[8] Perry, A.E. & Joubert, P.N., Rough-wall Boundary Layers in Adverse Pressure Gradients, Journal of Fluid Mechanics, 17, 1963, 193-211.

[9] Perry, A.E. & Li J.D., Experimental Support for the Attached-eddy Hypothesis in Zero-pressure-gradient Turbulent Boundary Layers, Journal of Fluid Mechanics, 218, 1990, 405-438.

[10] Schmitt, G., Bosch, C. & Mueller M., A Probabilistic Model for Flow Induced Localized Corrosion, CORROSION/2000, NACE International, Houston, Tx: 2000, Paper 49.

[11] Spalding, B.D., A Single Formula for the Law of the Wall, Journal of Applied Mechanics, 28, 1961, 455-458.

[12] Townsend, A.A., The Structure of Turbulent Shear Flow, Cambridge University Press, 1976.

[13] Wahidi, R.,Chakroun, W. & Al-Fahed, S, The Behavior of the Skin-friction Coefficient of a Turbulent Boundary Layer Flow over a Flat Plate with Differently Configured Transverse Square Grooves, Experimental Thermal and Fluid Science, 30(2), 2005, 141-152.

[14] Wei, T., Wilimarth, W.W., Reynolds-number Effects on the Structure of a Turbulent Channel Flow, Journal of Fluid Mechanics, 204, 1989, 57-95.

[15] Zheng, D.H., Che D.F. & Liu Y.H., Experimental Investigation on Gas-liquid Two-phase Slug Flow Enhanced Carbon Dioxide Corrosion in Vertical Upward Pipeline, Corrosion Science, 50(11), 2008, 3005-3020.