13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

Mean Flow Quantities for the Turbulent Boundary Layer over a k-type Rough Wall

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ABSTRACT

Measurement of mean flow quantities of the turbulent boundary layer over a k-type rough wall has been made in order to reveal its structure in comparison with those over a smooth wall and a d-type rough wall. In the present study, the wall shear stress was determined from the direct measurement method with a floating element device. It is observed that values of the local skin friction coefficient c_f depend on the relative roughness height k/δ (k is the roughness height and δ boundary layer thickness). Mean velocity profile normalized with the outer variables shows large deficit throughout the layer in comparison with the smooth wall and the d-type rough wall flows. The logarithmic velocity profile with the same slope as that in the smooth wall flow, namely, the Kármám constant remains 0.41 is confirmed. The dependence of the roughness function $\Delta U/u_\tau$ on a parameter $d_0 u_\tau/\nu$ (d_0 is the error in origin, u_τ the friction velocity, and ν the kinematic viscosity) is disagreement with those of the d-type rough wall. The turbulent intensity and Reynolds shear stress profiles normalized with the outer and the wall variables are not similar to those of both the smooth wall and the d-type rough wall flows.

INTRODUCTION

In generally, the distinction between a smooth wall and a rough wall is provided for the value of the roughness Reynolds number $k u_\tau/\nu$, and the rough wall that the value of the roughness Reynolds number is larger than 70 is referred to "a fully rough wall" (Nikuradse, 1933). Furthermore, the flow over the rough wall consisting of two-dimensional square ribs has been classified into two types (Perry et al., 1969). One is defined as a k-type rough wall of which error in origin d_0 is proportional to roughness height, and an another rough wall which d_0 is proportional to streamwise distance or boundary layer thickness is defined as a d-type rough wall. For the turbulent boundary layer over the d-type rough wall, the investigation performed by Osaka et al. (1984, 1991) and Tani (1987) have revealed the turbulent structure. On the other hand, the experimental study for the k-type rough wall turbulent boundary layer have been investigated by many researchers (e.g. Antonia and Luxton, 1971, Pineau et al., 1987, Liu et al., 1966), but our knowledge is not sufficient for its turbulent structure. Its one reason is that the wall shear stress providing the most important velocity scale to specify dynamics in a turbulent boundary layer has been determined by indirect methods (e.g. momentum balance method) by many experimental studies. Accordingly, it is acquired reliable data of the wall shear stress to investigate the structure for the turbulent boundary layer over the k-type rough wall.

In the present study, we will examine mean flow quantities using the wall shear stress determined by direct measurement with a floating element device for turbulent boundary layer over the k-type rough wall. In addition, the characteristics of mean flow quantities for the turbulent boundary layer over the k-type rough wall will be revealed in comparison with those of a smooth wall and a d-type rough wall turbulent boundary layers.

EXPERIMENTAL METHOD

The experimental study was conducted in a wind tunnel of open circuit type, which has a 4m-long working section with an inlet area of 260mm×500mm. Schematic flow field, coordinate system and nomenclature are shown in Fig. 1. The k-type rough wall consist of two-dimensional square ribs (3mm×3mm) arrayed on a wall with a pitch ratio of 4. Measurement was made at two relative roughness heights (ratio of roughness height k to boundary layer thickness δ) k/δ =0.044 and 0.076. Then, the momentum thickness Reynolds number R_θ (= $\theta U_1/\nu$, θ is the momentum thickness) varied from 1730 to 9700. The free steam turbulence level was about

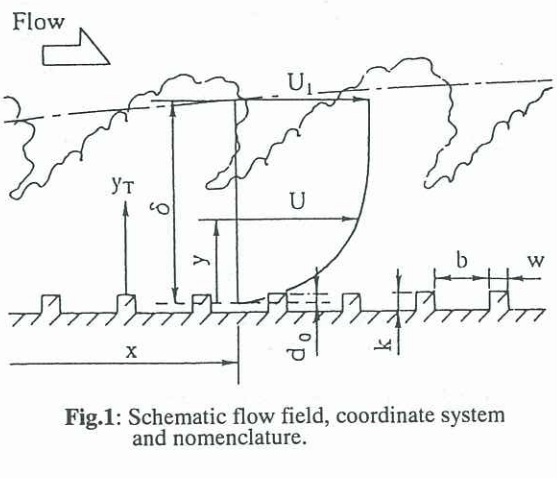

Fig.1: Schematic flow field, coordinate system and nomenclature.

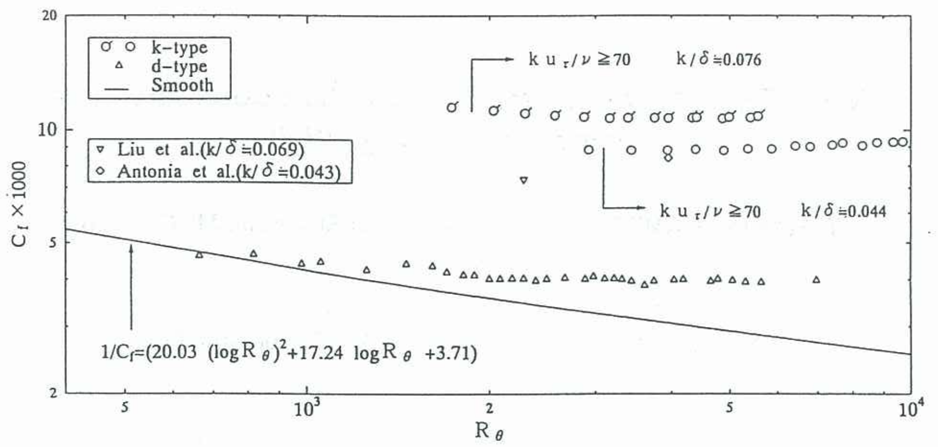

Fig.2: Local skin friction coefficient.

0.3%, and the static pressure along the working section was kept within $\pm 0.25\%$ of the free stream dynamic pressure. The wall shear stress was determined by direct measurement with a floating element device (Osaka et al., 1991), which has a circular surface with a diameter of 60mm. The roughness elements on the floating element are placed in symmetry with respect to centerline of the floating element surface. Measurement of velocity components was carried out with single and crossed hot wire probes (3.1 μm diameter and 0.62 mm sensor length tungsten filament were used) operated by constant temperature anemometers. Mean velocity and turbulent quantity profiles were measured in y_T-direction at the central position of a cavity between roughness elements, and these profiles were discussed for a fully rough regime.

RESULTS AND DISCUSSION

Figure 2 shows the local skin friction coefficient $c_f = \tau_w/(1/2\rho U_1^2)$($\tau_w$ is the wall shear stress, ρ the fluid density) determined by the direct measurement method. This figure contains results obtained by Antonia et al. (1971) and Liu et al. (1966) using indirect measurement methods for the boundary layer over a k-type rough wall with the same pitch ratio of 4. Also, results determined by direct measurement method for the boundary layer over a d-type rough wall (Osaka et al., 1984) and a smooth wall in our previous study (Osaka et al., 1998) are plotted. Our experimental data reasonably agree with that of Antonia et al. (1971), but do not with that of Liu et al. (1966). Also, it is observed that the value of c_f measured in the present k-type rough wall flow is much larger than those of the d-type rough wall (Osaka et al., 1984) and the smooth wall flows (Osaka et al., 1998), and evidently depends on the relative roughness height k/δ. Figure 3 shows mean velocity profiles normalized with the outer variables. In Fig.3 mean velocity of the other authors (Antonia et al., 1971 and Liu et al., 1966) and those measured in the d-type rough wall and the smooth wall flows (Osaka et al., 1984,1998) are plotted. The profile of the present k-type rough wall flow reasonably agrees with those of the other authors (Antonia et al., 1971 and Liu et al., 1966), and shows large deficit throughout the layer in comparison with both the d-type rough wall and the smooth wall flows (Osaka et al., 1984,1998). This means that the deficit of mean kinematic energy due to the wall shear stress in the k-type rough wall flow is much larger than both the d-type rough wall and the smooth wall flows. Figure 4 shows mean velocity profiles normalized with the wall variables. The friction velocity $u_\tau = \sqrt{\tau_w/\rho}$ is obtained

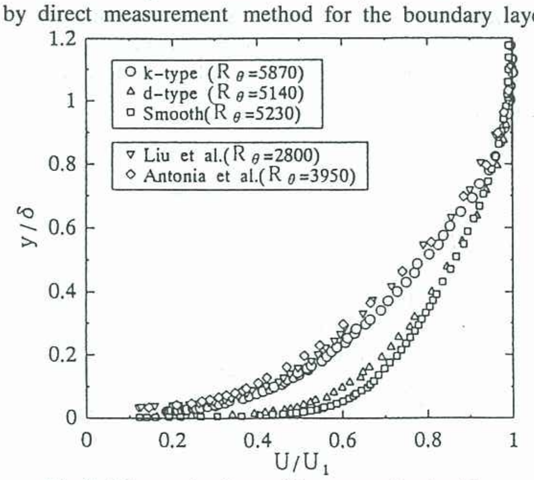

Fig.3: Mean velocity profiles normalized with the outer variables.

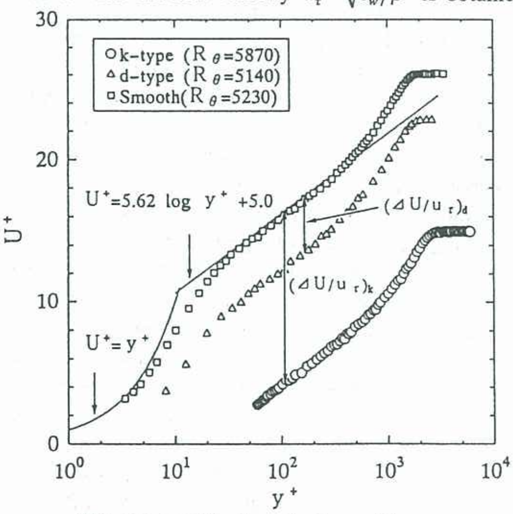

Fig.4: Logarithmic velocity profile.

using the value of the wall shear stress determined by the direct measurement. Also, the data measured for the d-type rough wall and the smooth wall flows (Osaka et al., 1984,1998) are plotted in Fig.4. In the present k-type rough wall flow, the logarithmic velocity profile with the same slope as that in the smooth wall flow, namely, κ is 0.41 is recognized, if the error in origin d_0 is relevantly determined. Roughness function in the present k-type rough wall flow takes larger value in comparison with that of the d-type rough wall flow. Next, the dependence of the roughness function $\Delta U / u_\tau$ on the Reynolds number $d_0 u_\tau / \nu$ based on the error in origin being a common representative length scale of both the k-type rough wall and the d-type rough wall flows is examined in Fig.5. In this figure the data of the other authors (Antonia et al., 1971 and Liu et al., 1966) are plotted. The solid lines represent experimental formulas proposed for the k-type rough wall and the d-type rough wall flows (Osaka et al., 1984), respectively:

$$\Delta U / u_\tau = 5.1\log(d_0 u_\tau / \nu) + 3.3$$

for the k-type rough wall,

$$\Delta U / u_\tau = 5.5\log(d_0 u_\tau / \nu) - 0.8$$

for the d-type rough wall.

Even in the k-type rough wall flow, the relationship between $\Delta U / u_\tau$ and $d_0 u_\tau / \nu$ can be correlated in a logarithmic form, but empirical constants, that is, the value of the slope and the additive constant of the logarithmic relation take smaller and larger values, respectively. These variations are caused by the differences of the thickness of the roughness sublayer and d_0 on roughness geometry for each type of rough wall (Perry et al., 1969). On the other hand, data of the other authors (Antonia et al., 1971 and Liu et al., 1966) agree with those for the present k-type rough wall flow. Figures 6 and 7 show streamwise turbulent intensity u_{rms} and Reynolds shear stress $-\overline{uv}$ profiles normalized with the outer variables. In these figures, results of the other authors (Antonia et al., 1971 and Liu et al., 1966) and data obtained measured in the d-type rough wall and the smooth wall flows (Osaka et al., 1984,1998) are plloted for cpmparision. For the u_{rms}/U_1 profile, the present result agree with that of Antonia et al.(1971), but do not with that of Liu et al.(1966). For the $-\overline{uv}/U_1^2$ profiles, large discrepancy of that of Antonia et al.(1971) from the present profile is observed. In comparison with the d-type rough wall and the smooth wall flows (Osaka et al., 1984,1998), the values of both the u_{rms}/U_1 and the $-\overline{uv}/U_1^2$ profiles for the k-type rough wall flow take larger value throughout the layer. From these results, it can be deduced that the production rate of turbulent energy in the k-type rough wall flow takes larger value compared with those of both the d-type rough wall and the smooth wall flows. Because the deficit of mean kinematic energy in the k-type rough wall flow takes larger value in the wall layer as seen in Fig.3. Figures 8 and 9 show streamwise turbulent intensity u_{rms} and Reynolds shear stress $-\overline{uv}$ profiles normalized with the wall variables. Also, in these figures as seen in Figures 6 and 7, data of the other authors (Antonia et al., 1971 and Liu et al., 1966) and those measured in the d-type rough wall and the smooth wall flows (Osaka et al., 1984,1998) are compared. In u_{rms}/u_τ component, the present profile agrees with that of Antonia et al. (1971), but do not with that of Liu et al. (1966). Furthermore, the present profile is not similar to those of both the d-type rough wall and the smooth wall flows. The maximum value being about u_{rms}/u_τ =2 for the present profile is much smaller than those both the d-type rough wall and the smooth wall flows. And, the distance from the wall y^+ for the maximum value in the present profile takes larger value

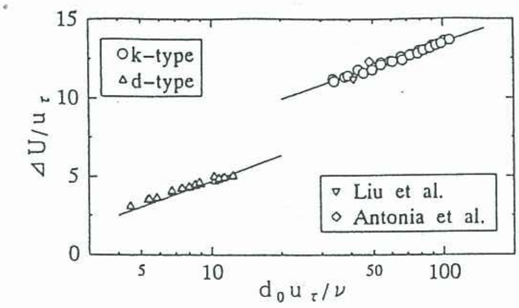

Fig.5: Roughness function.

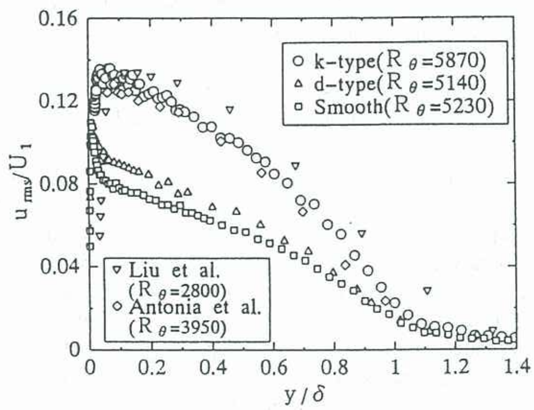

Fig.6:Streamwise turbulent intensity profile normalized with the outer variables.

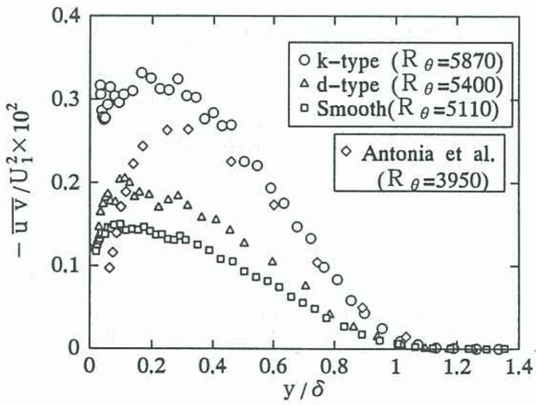

Fig.7: Reynolds shear stress profile normalized with the outer variables

in comparison with those (that is, nearly $y^+=15$) in the both the d-type rough wall and the smooth wall flows. In the $-uv/u_\tau^2$ profiles, the value of Antonia et al. (1971) is much smaller than that of the present profile. The constant stress layer in the $-uv/u_\tau^2$ profiles in the d-type rough wall and the smooth wall flows (Osaka et al., 1984,1998) does exist: $-uv/u_\tau^2 \sim 1$. However, the constant value of $-uv/u_\tau^2$ in the k-type rough wall flow takes smaller compared with those of both the d-type rough wall and the smooth wall flows (Osaka et al., 1984,1998). Accordingly, with the friction velocity u_τ determined by the direct measurement, the value of the present $-uv$ near the rough wall confirmed to be smaller value than unity. Also, this tendency has been reported by Antonia et al. (1971) with the indirect skin friction measurement. In such a case as the present rough wall made by the periodic array of two-dimensional roughness element with the large pitch ratio, we should take account of apparent shear stress $-<UV>$ (<*> denotes average over a one pitch length of roughness) caused by the wave of the mean streamline near the rough wall in the total shear stress.

CONCLUSION

We examined the mean flow quantities using c_f determined by the direct measurement for the turbulent boundary layer over the k-type rough wall. The experimental results provide the following conclusions.

(1) The value of c_f is much larger than those of both the d-type rough wall and the smooth wall flows, and depends on the relative roughness height k/δ.

(2) Mean velocity profile normalized with the outer variables shows large deficit throughout the layer in comparison with both the d-type rough wall and the smooth wall flows. The logarithmic velocity profile with the same slope as that in the smooth wall flow, namely, κ is 0.41 is recognized, if the error in origin d_0 is relevantly determined. In the k-type rough wall flow, the relationship between $\Delta U/u_\tau$ and $d_0 u_\tau/\nu$ correlates with the logarithmic form, but both the empirical constants of logarithmic relation are disagreed with those of the d-type rough wall flow.

(3) The values of streamwise turbulent intensity and Reynolds shear stress profiles normalized with the outer variables take much larger value in comparison with those of both the d-type rough wall and the smooth wall flows. Otherwise, the value of these profiles normalized with the wall variables take smaller value in the inner layer in comparison with those of both the d-type rough wall and the smooth wall flows.

ACKNOKWLEDGEMENTS

The authors acknowledge the financial support given by the Assistance of the Mazda Foundation for Research in Science and Technology.

REFERENCES

NIKURADSE, J.,"Strömungsgesetze in Rauhen Rohren", Forschungshefe,361,VDI; NACA Tech Men.,1292, 1933.

PERRY, A.E., SCHOFIELD, W.H. and JOUBERT, P.N., "Rough Wall Turbulent Boundary Layer", J. Fluid Mech., Vol. 37, No.2, 383-413,1969.

OSAKA H., NAKAMURA, I. and KAGEYAMA, Y., "Mean Flow Quantities for the Turbulent Boundary Layer over a d-type Rough Wall", JSME (in Japanese), Series B, Vol.50, No.458, 2299-2306,1984.

OSAKA, H. and MOCHIZUKI, S., "On the Turbulence Structure of the Boundary layer on d-Type Rough Surface", Experimental Heat Transfer, Fluid Mechanics, and Thermodynamics, Editors; KEFFER, J.K., SHAH, R.K. and Ganic E.N., 412-423, 1991.

ANTONIA, R.A. and LUXTON, R.E., "The Response of a Turbulent Boundary Layer to a Step Change in Surface Roughness; Part 1. Smooth to Rough", J. Fluid Mech., Vol.48, No.4, 721-761. 1971.

PINEAU, F., NGUYAN, V.D., DICKINSON, J. and BELANGER, J., "Study of Flow over a Rough Surface with Passive Boundary Layer Manipulators and Direct Wall Drag Measurement", AIAA Paper No 97-0357,1987.

LIU, C.K., KLINE, S.J. and JOHNSTON, J.P., "An Experimental Study of Turbulent Boundary Layer on Rough Walls", Stanford Univ. Mech. Eng. Thermoscience div. Rep. MD-15, 1966.

OSAKA, H., KAMEDA T. and MOCHIZUKI, S., "Re-Examination of the Reynolds-Number-Effect on the Mean Flow Quantities in a Smooth Wall Turbulent Boundary Layer", JSME Int.J., Series B, Vol.41, No.1, 123-129, 1998.

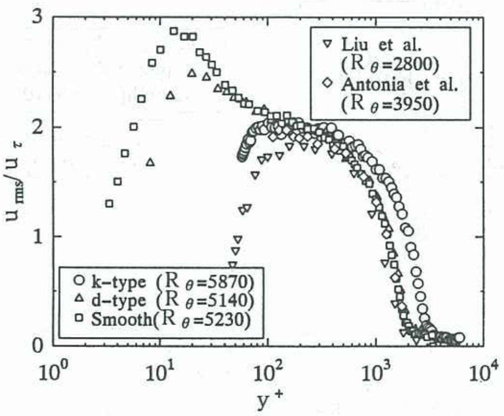

Fig.8:Streamwise turbulent intensity profile normalized with the wallr variables.

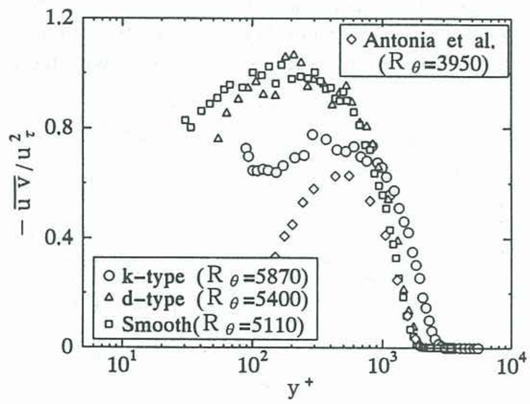

Fig.9: Reynolds shear stress profile normalized with the wall variables