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3-DIMENSIONAL MEASUREMENTS OF OPEN-CHANNEL FLOWS BY USING TWO-SETS OF LASER DOPPLER ANEMOMETERS

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SYNOPSIS

The Reynolds stresses are constituted by six components, i.e., $-\overline{uu}$, $-\overline{vv}$, $-\overline{ww}$, $-\overline{uv}$, $-\overline{uw}$ and $-\overline{vw}$. However, the Reynolds shear stress ($-\overline{vw}$) in open-channel flows has not been measured with high accuracy as yet. This is because such measurements of this stress are quite difficult. In this study, three-dimensional measurements in open-channel flows were conducted by the simultaneous use of two sets of laser Doppler anemometers(LDA). One is able to measure the U-V components, and the other is able to measure the U-W components. The Reynolds stress ($-\overline{vw}$) could be first measured with high accuracy. The streamwise velocities which were measured by U-V measurements and U-W measurements were in a good agreement with each other. The third-order moments of the velocity fluctuations coincided well with the results of DNS(Direct Numerical Simulation). A new empirical formula, involving the van Driest damping function, expresses the distribution of the spanwise turbulence intensity in the inner region.

INTRODUCTION

Turbulence measurements in open-channel flows by making use of total head tubes, electromagnetic current meters, hot-film anemometers, acoustic Doppler velocimetry(ADV) and laser Doppler anemometers(LDA) have been conducted by many researchers to investigate turbulent structures in open-channel flows. Ippen & Raichlen(1957) have used a total head tube for open-channel flow measurements. However, this device is not suitable for the direct measurements of velocity fluctuations, because the output of the device includes the effects of pressure fluctuations. Kisisel *et al.*(1973), Eckelmann(1974), Nakagawa *et al.*(1975) have used 2-components hot-film anemometers. A laser Doppler anemometer has been developed in the 1980's. Steffler *et al.*(1985) and Nezu & Rodi(1985) have used two-component LDA and they have investigated turbulent structures in open-channel flows. Nezu & Nakagawa(1993) have reviewed the turbulence-measurements techniques in the IAHR monograph.

By the way, turbulence is 3-dimensional fluctuations, inherently. Therefore, the Reynolds stresses are constituted by six components such as $-\overline{uu}$, $-\overline{vv}$, $-\overline{ww}$, $-\overline{uv}$, $-\overline{uw}$ and $-\overline{vw}$. In which, u, v and w are the turbulent fluctuations in the streamwise, vertical and spanwise directions, respectively. The Reynolds stress of $-\overline{vw}$ in open channel flows has not been measured with high accuracy as yet, because the measurements of $-\overline{vw}$ are impossible by making use of conventional 2-components anemometers and recently developed particle-image velocimetry(PIV).

In this study, three-dimensional measurements in open-channel flows were conducted by the simultaneous use of two sets of laser Doppler anemometers. The Reynolds stress ($-\overline{vw}$) could be measured successfully with high accuracy for the first time in this research.

THEORETICAL CONSIDERATIONS

In 2-D uniform open-channel flows, the turbulence intensities u'/U_*, v'/U_* and w'/U_* are described by Nezu's empirical formulae, as follows (see Nezu & Nakagawa 1993):

$$\frac{u'}{U_*} = D_u \exp(-\lambda_u \xi) \tag{1}$$

$$\frac{v'}{U_*} = D_v \exp(-\lambda_v \xi) \tag{2}$$

$$\frac{w'}{U_*} = D_w \exp(-\lambda_w \xi) \tag{3}$$

in which, $\xi \equiv y/h$ and h is the flow depth. u', v' and w' are the RMS values of the turbulent fluctuations in the streamwise(x), vertical(y) and spanwise(z) directions, respectively. U_* is the friction velocity, which is very important velocity scale in turbulence theory. Turbulence measurements in 2-D uniform open-channel flows were conducted by Nezu(1977) by the use of a two-component hot-film anemometers. He proposed that the empirical constants were nearly equal to D_u=2.30, D_v=1.27, D_w=1.63 and $\lambda_u = \lambda_v = \lambda_w$=1.0. Later, Nezu & Rodi(1986) have conducted turbulence measurements with a two-component forward-scattered laser Doppler anemometer using two-color Ar-ion laser beams. They indicated that the empirical constants in Eqs.(1)-(3) were given by D_u=2.26, D_v=1.23, λ_u=0.88 and λ_v=0.67. In the buffer layer ($5 \le y^+ \le 30$), Eq.(1) is modified in the followings:

$$\frac{u'}{U_*} = D_u \exp\left(-\lambda_u \frac{y^+}{R_*}\right)\Gamma + Cy^+(1-\Gamma) \tag{4}$$

$$\Gamma = 1 - \exp\left(-\frac{y^+}{B_{ut}}\right) \tag{5}$$

in which, $R_* \equiv hU_*/\nu$ and C is the empirical coefficient. $y^+ \equiv yU_*/\nu$ is the non-dimensional coordinate by the inner variables. Nezu & Rodi(1986) have found experimentally that C is constant value of 0.3 in 2-D open-channel flows, irrespective of the Reynolds and Froude numbers. Recently, Onitsuka & Nezu(1998) have measured the viscous sublayer($y^+ \le 5$) and buffer layer of 2-D open-channel flows by making use of an innovative two-component fiber-optic laser Doppler anemometer and proposed the empirical formula, as follows:

$$\frac{v'}{U_*} = D_v \exp\left(-\lambda_v \frac{y^+}{R_*}\right)\Gamma \tag{6}$$

$$\Gamma = 1 - \exp\left(-\frac{y^+}{B_{vt}}\right) \tag{7}$$

Onitsuka & Nezu(1998) have indicated then that the value of B_{vt} is nearly equal to 26. In contrast, the distributions of the spanwise turbulent intensity very near the wall have not been investigated at all, because this measurements are very difficult even with an LDA system.

EXPERIMENTAL EQUIPMENT AND DATA PROCESSING

The experiments were conducted in a 10-m-long, 40-cm-wide, and 50-cm-deep tilting flume as shown in Fig.1. In this water flume, the discharge Q can be automatically controlled by a personal computer in which the rotation speed of a water-pomp motor involving an inverter transistor is controlled by the feedback from the signals of an electromagnetic flow-meter. The bed-wall and side-wall are made of optical glass.

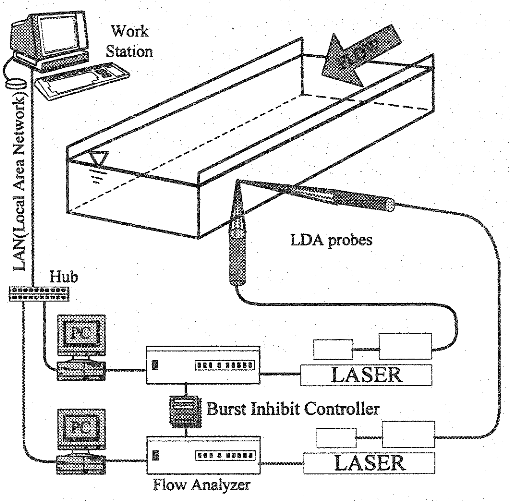

Fig.1 Experimental Flume and LDA System

Three components of instantaneous velocities, i.e., the streamwise velocity $\tilde{u}(t) = U + u(t)$, the vertical velocity $\tilde{v}(t) = V + v(t)$ and the spanwise velocity $\tilde{w}(t) = W + w(t)$, were measured with two sets of two-component fiber-optic LDAs. One LDA fiber probe was located at side of the channel, which can measure the instantaneous streamwise velocity, $\tilde{u}(t)$ and vertical velocity, $\tilde{v}(t)$ (U-V measurements). The other probe was located below the channel bottom, which can measure the instantaneous streamwise velocity, $\tilde{u}(t)$ and the instantaneous spanwise velocity, $\tilde{w}(t)$ (U-W measurements). The clock of these two LDAs is synchronized by a burst inhibit controller. The LDAs were located at 8m downstream of the channel entrance so that the flow was fully developed. The LDA probes were moved by the three-dimensional traversing mechanisms that are attached directly with the flume. The accuracy of these traversing mechanisms was within 1/100mm. The measurements very near the wall, i.e., up to y =0.1mm, can be conducted very carefully and accurately.

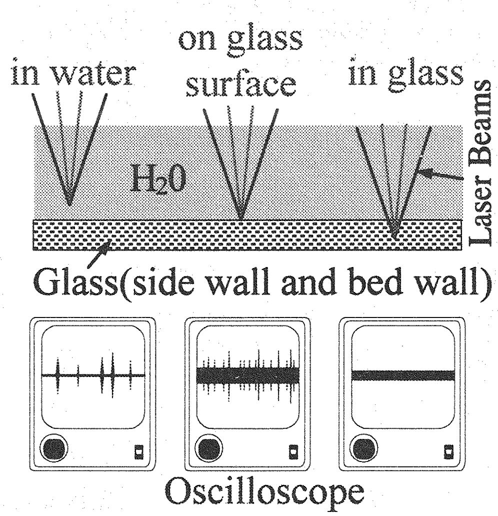

Fig.2 Bust Signals of Each Setup Condition

All of output signals of the LDAs were recorded in a digital form with a sampling frequency more than 100(Hz) into a HDD of the personal computer. After the experiments, all of the experimental data were transferred to the workstation through the LAN network.

It is necessary to control the coincidence of the measuring points of each LDAs in order to measure the Reynolds stress ($-\overline{vw}$). The set-up of coincidence of the measuring points was made by three steps, as follows:

Coincidence of x-z-plane

Weather the measuring point is located in the water or on the glass surface or in the glass, the each burst signals are different, as one can see easily by an oscilloscope as shown in Fig.2. Therefore, the measuring points of each two set of LDAs can be set on the bed-wall at which y =0 as shown in Fig.3.

Coincidence of x-y-plane

When a rectangular glass obstacle was put on the bed-wall, the measuring point of each two set of LDAs can be set on the surface of the rectangular glass obstacle at which z =0.

Coincidence of y-z plane

Finally, the measuring points of each two set of LDAs can be set on the surface of the rectangular glass obstacle at which x =0.

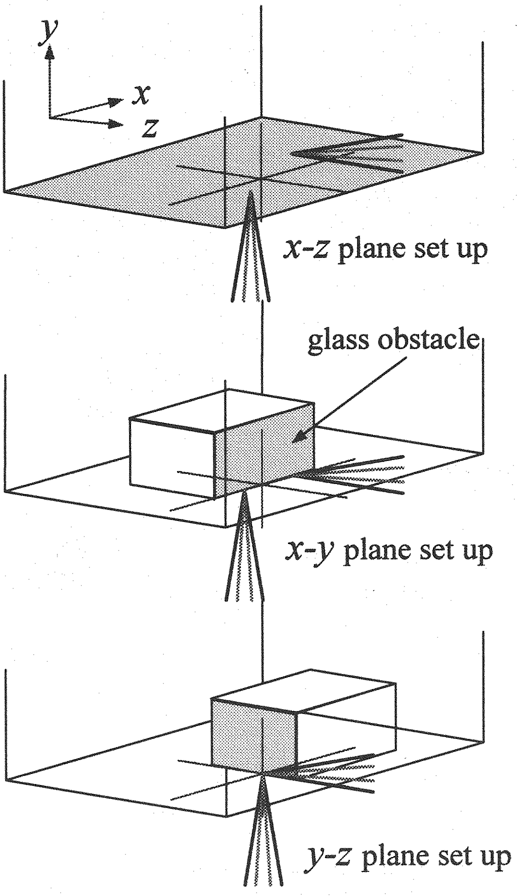

Fig.3 Coincidence of Measuring Points

Hydraulic Conditions

Experimental conditions are shown in Table 1. In which, $Fr \equiv U_m / \sqrt{gh}$ is the Froude number, $Re \equiv U_m h / \nu$ is the Reynolds number on the basis of the bulk mean velocity U_m. g is the gravitational acceleration and ν is the kinematic viscosity. U_{*v} (by U-V measurements) and U_{*w} (U-W measurements) are the friction velocities which were calculated by the by the log-law as follows:.

Table 1 Hydraulic Condition

case	h cm	Fr	Re $\times 10^3$	R_*	U_{*v} cm/s	U_{*w} cm/s
R148		0.06	2.0	148	0.30	0.29
R251	5.0	0.11	4.0	251	0.51	0.50
R454		0.23	8.0	454	0.92	0.90

$$U^+ = \frac{1}{\kappa} \ln y^+ + A \qquad (8)$$

in which $U^+ \equiv U / U_*$. Nezu & Rodi(1986) indicated that the Karman constant κ (=0.41) and the integration constant A (=5.3) are universal values irrespective of the Reynolds and Froude numbers in the case of 2-D uniform flows. It was found that the experimental values of friction velocities U_{*v} and U_{*w} coincided well with each other, as judged from Table 1.

RESULTS AND DISCUSSION

Verification of the Coincidence of the Measuring Points

Fig.4 shows the distributions of the streamwise velocities, which were measured by the U-V measurements and the U-W measurements. These velocities agree well with each other. Therefore, the friction velocities U_{*v} and U_{*w}, which were evaluated by the log-law(8), also agree well with each other.

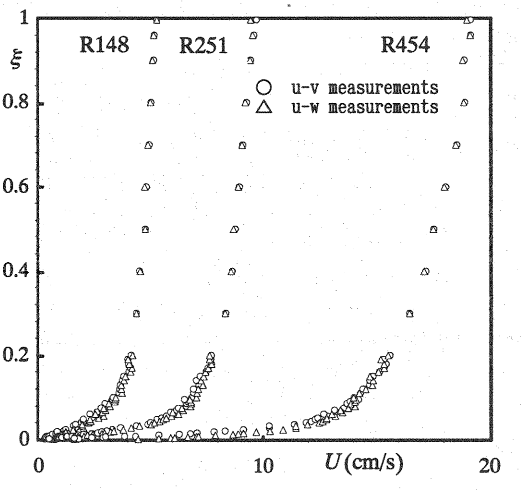

Fig.4 Distributions of Streamwise Velocities

In the case of 2-D uniform flow, the value of the spanwise Reynolds stress $-\overline{uw}$ must be equal to zero at the center of the channel. Fig.5 shows the distributions of the spanwise Reynolds stress $-\overline{uw}$. Although there is some scatter in data, no systematic deviation can be seen. Therefore, the flows in this study are 2-dimensional uniform flows.

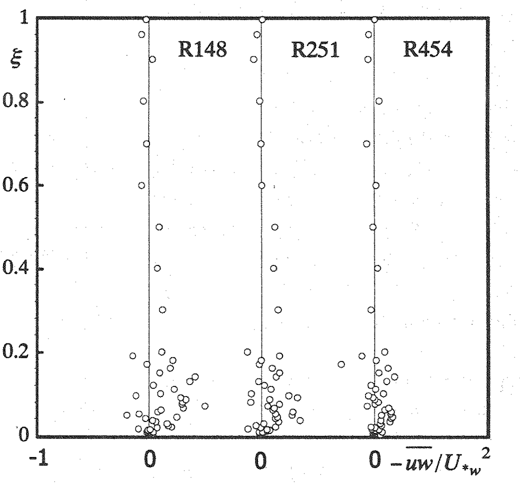

Fig.5 Distributions of Spanwise Reynolds Stress

Fig.6 shows the time series of the instantaneous streamwise velocity $\tilde{u}_v$ measured by the U-V measurements, the instantaneous streamwise velocity $\tilde{u}_w$ measured by the U-W measurements, the instantaneous vertical velocity $\tilde{v}$, the instantaneous spanwise velocity $\tilde{w}$, the instantaneous vertical Reynolds stress $-uv$ and the instantaneous spanwise Reynolds stress $-uw$. The behavior of the time series of $\tilde{u}_v$ and $\tilde{u}_w$ are almost same. It can be seen that when the streamwise velocity takes a minimum value, the vertical velocity takes a maximum value and vice versa. These are caused by the bursting phenomena. The time series of the instantaneous Reynolds stress $-vw$ are also included in Fig.6. This Reynolds stress is calculated by the instantaneous vertical velocity measured by the U-V measurements and the instantaneous spanwise velocity measured by the U-W measurements.

Reynolds Stress of $-\overline{vw}$

The vorticity equation in uniform channel flows involves not only the turbulence intensities v' and w', but also the Reynolds stress $-\overline{vw}$. Nezu & Nakagawa(1984) estimated all terms in the vorticity equation except for the Reynolds stress term. The Reynolds stress $-\overline{vw}$ in open-channel flows has not

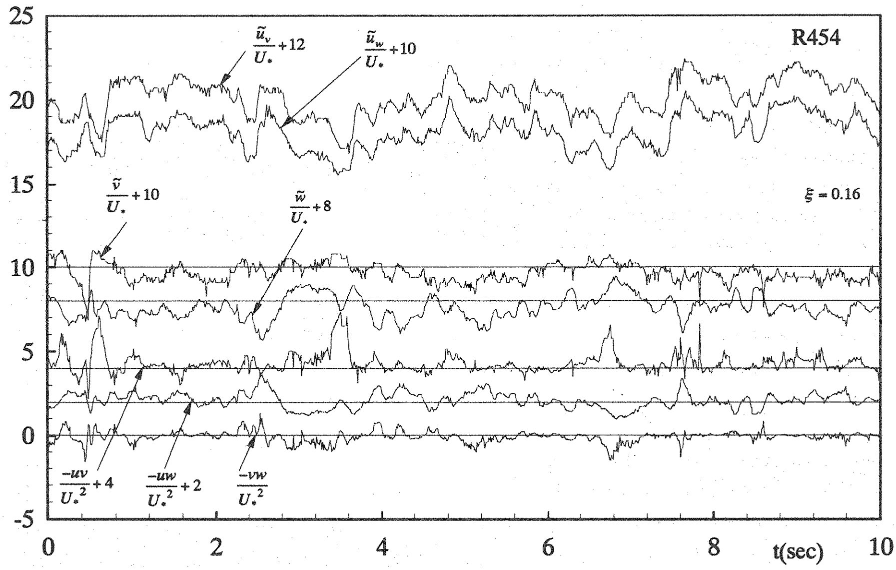

Fig.6 Time Series of Various Instantaneous Fluctuations

been measured with high accuracy as yet. Therefore, it is quite important to measure the Reynolds stress $-\overline{vw}$ to investigate the turbulence structures in open-channel flows. Fig.7 shows the distributions of the time-averaged Reynolds stress $-\overline{vw}$ normalized by the friction velocity. In the case of 2-D uniform flow, the value of the Reynolds stress $-\overline{vw}$ must be zero at the center of the channel. The experimental values of $-\overline{vw}$ deviate from zero near the bed to some extent. However, the deviation is considerably small.

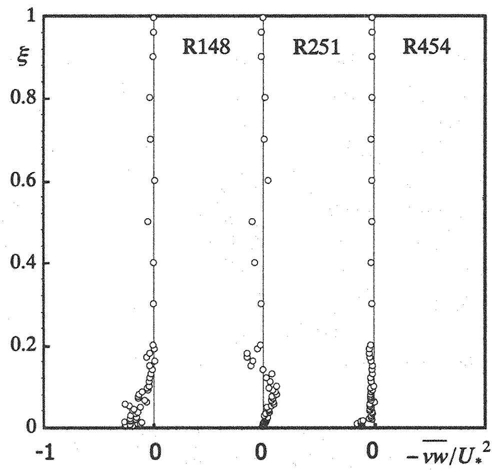

Fig.7 Distribution of Reynolds Stress $-\overline{vw}$

Spanwise Turbulence Intensity near the Bed

Nezu & Rodi(1986) have measured the streamwise turbulence intensity u' very near the wall and indicated that the coefficients of C and B_{ut} in Eq.(4) are constant values in 2-D open-channel flows, irrespective of the Reynolds and Froude numbers. Recently, Onitsuka & Nezu(1998) have measured the viscous sublayer and the buffer layer of 2-D open-channel flows by making use of an LDA and have proposed the empirical formulae(6) and (7). In contrast, the distributions of the spanwise turbulent intensity w' very near the bed have not been measured as yet. In the present study, the measurements of the spanwise turbulent intensity w' very near the bed could be achieved by use of a fiber-optic LDA and high accurate traversing system. Fig.8 shows the distributions of the spanwise turbulent intensity w' normalized by the friction velocity U_* including the viscous sublayer and the buffer layer, together with the Nezu's(1977) empirical formula(3) which is described by a monotonic ally decreasing curved line. It can be seen that the distributions of the spanwise turbulent intensity are expressed well by the Nezu's(1977) empirical formula(3) over the buffer layer. In contrast, they deviate from Eq.(3) near the bed due to the viscous effects. A new empirical formula is proposed then as follows:

$$\frac{w'}{U_*} = D_w \exp\left(-\lambda_w \frac{y^+}{R_*}\right)\Gamma \quad (9)$$

$$\Gamma = 1 - \exp\left(-\frac{y^+}{B_{wt}}\right) \quad (10)$$

Eq.(9) approaches to zero at the bed wall. Eq.(9) is plotted in Fig.8 by a curved line. It can be said that the distributions of the spanwise turbulent intensity are described well by Eq.(9) near the wall.

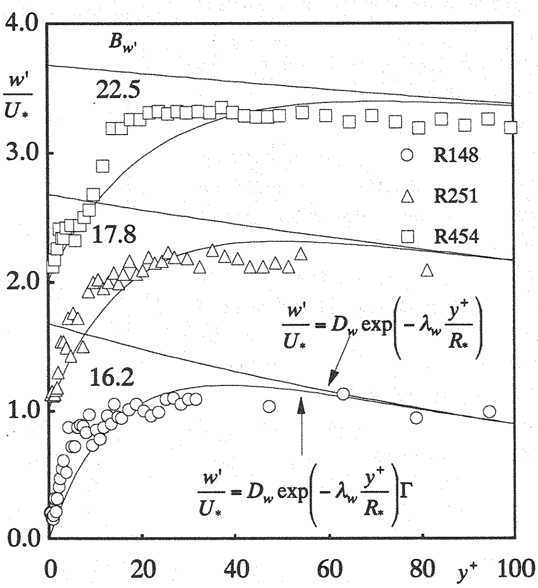

Fig.8 Distribution of the Spanwise Turbulence Intensity very near the Bed

Third-Order Moments of Turbulence

The third-order moments of the turbulence are very important statistics because they have a relationship with the bursting phenomena as pointed out by Nakagawa & Nezu(1977) and also because the third moments $\overline{uuv}$ and $\overline{vvv}$ constitute the diffusion terms in turbulence energy equation. Figs.9 and 10 show the distributions of $\overline{uuv}$ and $\overline{vvv}$ normalized by the friction velocity, together with Kim *et al.* s'(1987) DNS (Direct Numerical Simulation) data in a closed-channel flow under the condition that the R_* is 400 and R_e is 8000. Although there is some scatter in data, no systematic deviation can be seen. The present data coincide well with DNS database. Therefore, it can be said that characteristics of the third-order moments near the wall in open-channel flows agree with those in closed-channel flows.

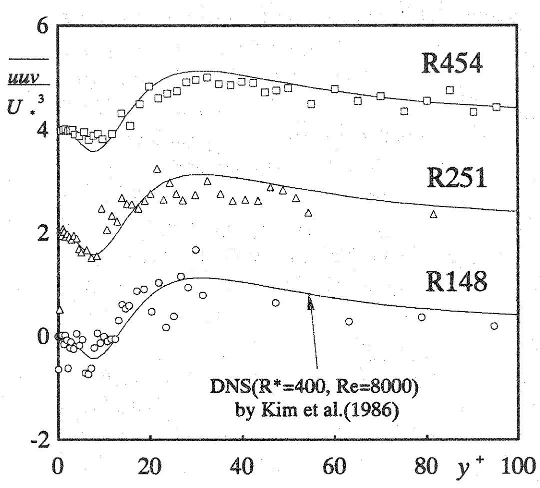

Fig.9 Distributions of the $\overline{uuv}$

CONCLUSIONS

Three-dimensional measurements in open-channel flows were conducted by making use of two sets of innovative fiber optic laser Doppler anemometers. The streamwise velocities which were measured by the U-V measurements and the U-W measurements were in a good agreement with each other. The Reynolds stress ($-\overline{vw}$) could be first measured successfully with high accuracy. A new empirical formula, which can describe the spanwise turbulence intensity distributions in the inner region, is proposed then. Finally, the third-order moments of the velocity fluctuations agree well with the results of DNS database. It was found that the characteristics of the third-order moments near the wall in open-channel flows coincide with those in closed-channel flows.

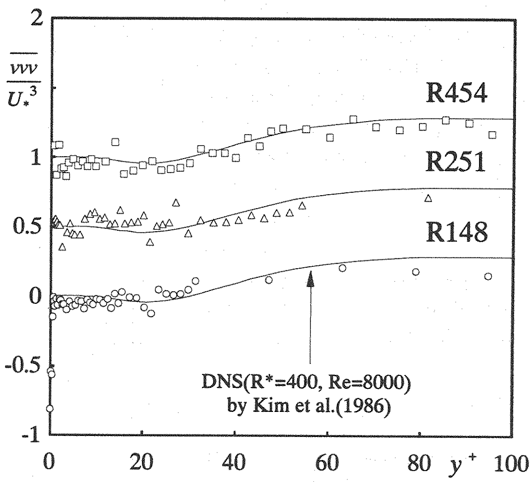

Fig.10 Distributions of the $\overline{vvv}$

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