532.526:532.517.4

Paper No. 174-5

Turbulent Boundary Layers Disturbed by Two-dimensional Bluff Bodies*

(Characteristics of Turbulence)

By

Yasuhiro SUZUKI**, Masaru KIYA*** and Mikio ARIE****

Presented in this paper are the results of an experimental investigation of a two-dimensional turbulent boundary layer disturbed by a rectangular cylinder attached to a smooth plane wall with the axis normal to the direction of the main flow. Turbulent energy, turbulent shear stress, probability density of fluctuating velocities, spectra of stream-wise turbulent energy, intermittency factor, correlation function and integral scales of turbulent eddies are measured in detail with constant-temperature hot-wire anemometers. The main features of the disturbed turbulent boundary layers are also discussed in comparison with those of equilibrium turbulent boundary layers.

1. Introduction

In the previous paper⁽¹⁾, an empirical scheme was presented to describe the time-averaged velocity profile of relaxing turbulent boundary layers behind rectangular cylinders of various heights, which were attached to a plane wall. Two groups of parameters were used to correlate Coles' empirical formula for mean velocity profile in turbulent boundary layers with the distance downstream of the cylinders: the first group was the parameters to define the geometrical shape of the rectangular cylinders relative to the thickness of the undisturbed turbulent boundary layer, i.e., b/h and h/δ_0 (the meanings of the symbols are the same as in Ref.(1) unless otherwise stated), and the second one was $U_\infty \delta_0/\nu$ and u_τ/U_∞ which represented the characteristics of the undisturbed boundary layer.

The characteristics of the relaxing boundary-layer flow behind an obstacle are highly complicated owing to the turbulence in the shear layer separated from the obstacle. This sort of flow is frequently encountered in our environments or in engineering applications: diffusion of heat or pollutant in the downstream vicinity of buildings and structures, and the effect of upstream building on the aerodynamic characteristics of downstream ones may belong to the category of this problem. In order to meet these practical applications, the turbulent structures involved should also be understood in addition to the time-averaged flow properties.

Although turbulent boundary layers

disturbed by obstacles were treated by several investigators⁽²⁾, statistical properties of such boundary layers have not yet been satisfactorily clarified. The structure of the disturbed boundary layers is not in dynamical equilibrium in relaxing regions, but it must approach an equilibrium state in the region sufficiently downstream. From the practical point of view, the properties of the relaxing boundary layers, i.e. the boundary layers developing towards the equilibrium state, are also important. However, only insufficient data of this nature seem to be available. On the other hand, various schemes for calculating the time-averaged and turbulent properties of boundary layers have been developed since 1960's with some success. However, since these calculation schemes rely heavily on experimental data collected from the characteristics of equilibrium turbulent boundary layers, they generally yield rather poor prediction for the relaxing boundary layers such as treated in the present investigation. Therefore, a wide data base for some typical nonequilibrium turbulent boundary layers must first be established before the available calculation schemes could be modified to be applicable to the nonequilibrium case of boundary layers.

In view of the foregoing discussion, the present paper experimentally describes detailed nature of turbulence in the relaxing boundary layers behind rectangular cylinders of various geometrical shapes, their height relative to the thickness of the original boundary layer being systematically changed. Measurements include turbulent kinetic energy, Reynolds shear stress, probability density function, autocorrelation function, intermittency factor, etc.

* Received 20th October, 1978.

** Instructor, Faculty of Engineering Hokkaido University, Sapporo.

*** Associate Professor, the same as above.

**** Professor, the same as above.

2. Experimental equipment and procedures

2.1. Turbulent velocity component and its spectrum

Linearized constant-temperature hot-wire anemometer was used to measure the turbulent velocity fluctuation. The turbulent velocity components in the x, y and z directions, i.e. u' , v' and w' , were measured with I-, X- and V-type of hot-wire probes, respectively. The diameter of the probes was 5.0 microns and their working length was 1.5 mm. The frequency response of the entire hot-wire system was flat from Dc to 10 kHz, calibration being made by means of a square wave. The hot-wire signal was recorded on an analogue data recorder in FM mode with a tape speed of 60 in./sec for later statistical analysis.

Spectrum analysis of the turbulent fluctuating velocity was made by an audio frequency analyzer consisting of 1/3 oct. filters with central frequencies ranging from 40 Hz to 31.5 KHz. In higher frequency range, where the frequency band becomes wider, the noise amplitude at each central frequency was calibrated with a white-noise generator.

2.2. Correlation function and probability density

Correlation function and probability density of the fluctuating velocities were measured by real time correlation and probability analyzer (SAI 42A). Since this is a digital analyzer with AD converters installed, the aliasing errors were avoided by passing the hot-wire signal through a low-pass filter with an upper frequency of 5 KHz and a damping of 24 db/oct. Sampling interval was set at 200 μ sec and the total integration time for the calculation of the probability density function and the correlation function was 13.1 sec.

2.3. Intermittency factor

An electronic device to measure the intermittency factor was constructed by the authors, the principle of its operation being essentially the same as that used by Corrsin and Kistler⁽³⁾. The electronic calibration of the intermittency meter was performed by using a burst generator. In order to choose the optimum threshold level for actual measurements, hot-wire signals were compared with the trigger-circuit output on a two-beam memory synchroscope. The error in the measurement of the turbulent interval from the trigger output was reduced by employing a voltage-to-frequency converter.

2.4. Wind tunnel and test cylinders

The experiments were conducted in a low-speed closed-circuit wind tunnel at the Faculty of Engineering, Hokkaido University. The dimensions of the wind-tunnel test-section are 1.5 m wide, 1.2 m high (nominal)

and 6.0 m long. Some details of the wind tunnel are given in Ref.(1). The free-stream velocity was maintained constant at 12.5 m/sec. The rectangular cylinders were mounted on the tunnel floor and extended over the width of the tunnel (1.5 m), a fully developed turbulent boundary layer existing along the tunnel floor. The geometrical shape of the rectangular cylinders can be described by the width-to-height ratio b/h and the ratio of the height to thickness δ_0 of the undisturbed boundary layer at the location of the cylinders. In the present paper, the experimental results for the cases of $b/h = 2/3$, $h/\delta_0 = 0.188$ and 0.375 and $b/h = 3/2$, $h/\delta_0 = 0.125$ and 0.25 will be presented.

3. Results and discussions

3.1. Time-averaged velocity profile and intermittency factor

The disturbance caused by a two-dimensional obstacle in the turbulent boundary layer will be relaxing in the downstream direction. Therefore, the order of magnitude of the disturbance has to be quantitatively taken into account in the description of the velocity profile. Since the scheme to correlate the velocity profile with the disturbances is already presented in Ref.(1), only the relevant features of the velocity profile in the disturbed turbulent boundary layers will be described here. Coles' wake function was employed to represent the time-averaged velocity profile in the disturbed boundary layer, i.e.

$$u/u_t = (1/\kappa) \ln(yu_t/\nu) + C + (\Pi/\kappa) w(y/\delta)$$

The value of constant C was not equal to 5.0, i.e. the value for equilibrium turbulent boundary layers along a smooth flat surface. This fact implies that the effect of the disturbance manifests itself also in the inner part of the boundary layer. Furthermore, the profile parameter Π has larger values than that of the equilibrium layers in which the value of Π is equal to 0.55. One of the prominent features of the turbulent boundary layers disturbed by a two-dimensional obstacle was a wider region of logarithmic velocity profile as compared with the equilibrium boundary layers.

The intermittent nature of turbulence in the turbulent boundary layers has been investigated by various researchers: Corrsin and Kistler⁽³⁾, Townsend⁽⁴⁾, Klebanoff⁽⁵⁾, Fiedler and Head⁽⁶⁾, Kovasznay et al.⁽⁷⁾ and Townsend⁽⁸⁾ among others. These investigators disclosed a strong relationship among the intermittency in the turbulent boundary layer, the rate of entrainment and the irregularities of the superlayer. Since turbulent and non-turbulent fluids pass a point one after another in the intermittent region, the time-averaged velocity u can be expressed as a weighted sum of the turbulent-fluid velocity u_t and the non-turbulent fluid velocity u_p ;

$$u = \gamma u_t + (1 - \gamma) u_p \quad \dots\dots\dots (1)$$

where γ is an intermittency factor. The intermittency factor is defined as the fraction of time of the turbulent flow to the total measuring time. Figures 1 and 2 show the intermittency factor γ and the burst frequency f_γ in the disturbed turbulent boundary layer as functions of y/δ . The distribution of γ shown in Fig. 1 can approximately be expressed by an empirical formula originally proposed by Klebanoff⁽⁵⁾;

$$\gamma = (1/2)[1 - \text{erf}((y - \bar{Y})/(\sqrt{2\pi}\sigma))] \dots\dots (2)$$

where $\bar{Y}$ is the mean location of the fluctuating superlayer and σ is its standard deviation. According to the experimental results of Klebanoff⁽⁵⁾, the values of $\bar{Y}$ and σ are 0.78 δ and 0.14 δ , respectively, for equilibrium turbulent boundary layers with zero pressure gradient developing along a smooth plane wall. Kovaszny et al.⁽⁷⁾ obtained the values of $\bar{Y} = 0.8\delta$ and $\sigma = 0.15\delta$ for an equilibrium boundary layer. For disturbed boundary layers treated here, $\bar{Y}/\delta$ takes a constant value between 0.75 and 0.8 while σ/δ varies somewhat systematically in a range between 0.13 and 0.25 as will be seen in Fig. 3. Larger values of σ/δ in the disturbed boundary layers than in the equilibrium boundary layers along a flat plate are in agreement with the findings of Fiedler and Head⁽⁶⁾. The value of σ/δ they obtained after reattachment is also larger than that of an equilibrium turbulent boundary layer with the same value of the shape factor H .

Since the superlayer is a boundary between the turbulent and non-turbulent fluids, the value of σ in Eq.(2) can be considered as a scale of large eddies in the y -direction. It is also possible to determine a scale of eddies in the streamwise direction by means of the burst frequency f_γ . Since the average time interval

Fig. 1 Intermittency factor γ across relaxing turbulent boundary layer.

between successive turbulent bursts is f_γ^{-1} , the scale of eddies in the streamwise direction can be obtained once the phase velocity of the eddies U^* is known. According to Kovaszny et al.⁽⁷⁾, the phase velocity at the location corresponding to $\gamma = 0.5$ can be set equal to the free-stream velocity within the error of 5 to 7 percent. If this approximation is employed, the average streamwise length of turbulent bursts at the location of $\gamma = 0.5$ is given by

$$L_\gamma = \gamma U^* / f_\gamma \quad \text{or} \quad L_{\gamma=0.5} = \gamma U_\infty / f_\gamma \dots\dots (3)$$

The ratio of σ to $L_{\gamma=0.5}$ can thus be interpreted as a parameter which represents the roughness of the superlayer. Figure 3 shows the values of σ/δ and $\sigma/L_{\gamma=0.5}$ plotted against the nondimensional streamwise coordinate x/h . The value of $\sigma/L_{\gamma=0.5}$ was found to be nearly equal to 0.23 for equilibrium turbulent boundary layers and wall jet⁽⁹⁾. However, as shown in Fig. 3, $\sigma/L_{\gamma=0.5}$ is higher than this value, thus showing that the superlayer is more rougher in the relaxing boundary layers than in equilibrium ones.

Fig. 2 Intermittency frequency f_γ across relaxing turbulent boundary layer.

Fig. 3 Average length $L_{\gamma=0.5}$ of turbulent burst and width of superlayer σ .

3.2. Turbulent energy and Reynolds shear stress

Root-mean-square values of the fluctuating velocity components $\overline{u'}$, $\overline{v'}$, $\overline{w'}$ and Reynolds shear stress $-\rho\overline{u'v'}$ are plotted in Fig. 4 as functions of y/δ_0 , experimental results of Klebanoff⁽⁵⁾ being included for the purpose of reference. The components $\overline{u'}$ and $\overline{v'}$ were detected by the X-wire probe and the component $\overline{w'}$ by the V-wire probe. Individual hot-wires of each probe were set at an angle of 45° to the mean-flow direction. The value of the Reynolds shear stress $-\rho\overline{u'w'}$ was found to be negligibly small in the boundary layers. Since the distributions of the turbulent quantities $(\overline{u'^2})^{1/2}$, $(\overline{v'^2})^{1/2}$, $(\overline{w'^2})^{1/2}$ and $-\overline{u'v'}$ are in good agreement with those obtained by Klebanoff⁽⁵⁾, the undisturbed turbulent boundary layer can be taken as a fully-developed equilibrium turbulent boundary layer with regard to the turbulent properties.

The turbulent intensities and Reynolds shear stress of the relaxing turbulent boundary layers downstream of a rectangular cylinder were measured in the same way as described just above.

Figure 5 shows the distributions of the turbulent quantities in a relaxing boundary layer at two typical distances downstream of the cylinder. In the case of equilibrium turbulent boundary layers along a smooth or rough wall, the magnitude of rms values of velocity fluctuations has a decreasing order of $(\overline{u'^2})^{1/2}$, $(\overline{w'^2})^{1/2}$ and $(\overline{v'^2})^{1/2}$. However, in the vicinity of the cylinders, these values show a decreasing order of $(\overline{u'^2})^{1/2}$, $(\overline{v'^2})^{1/2}$ and $(\overline{w'^2})^{1/2}$ except in the region close to the wall. The same tendency was observed by Arie and Rouse⁽¹¹⁾ who measured the distribution of the turbulent intensities behind a normal flat plate with the tail plate immersed in a uniform flow. Therefore, it can be said that the effects of turbulence in the shear layer separated from

Fig. 4 Distributions of rms turbulent velocities $\sqrt{\overline{u'^2}}$, $\sqrt{\overline{v'^2}}$, $\sqrt{\overline{w'^2}}$ and Reynolds shear stress $-\overline{u'v'}$ in the undisturbed boundary layer at the location of rectangular cylinders.

the cylinder surface remain to be observed within a considerable distance downstream of the reattachment point of the shear layer. As seen in Fig. 5, the order of $(\overline{v'^2})^{1/2} > (\overline{w'^2})^{1/2}$ changes to that of $(\overline{w'^2})^{1/2} > (\overline{v'^2})^{1/2}$ in the region far downstream, which is the case of equilibrium turbulent boundary layers along a plane wall.

Figure 6 shows the variations of the turbulent kinetic energy $\overline{q'^2}$ in the downstream direction for a few values of the ratio h/δ_0 . The turbulent kinetic energy $\overline{q'^2}$ is defined by

$$\overline{q'^2} = \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \quad \text{..... (4)}$$

This figure demonstrates how the turbulent kinetic energy decreases in the downstream direction. In order to quantitatively clarify the process of decay of turbulent motions, the total amount of turbulent kinetic energy E is introduced by the definition

$$E = (1/\delta) \int_0^\delta \overline{q'^2} dy \quad \text{..... (5)}$$

Figure 7 shows the variations of E and $(\overline{q'^2})_{peak}$ in the downstream direction. Here, $(\overline{q'^2})_{peak}$ denotes the maximum value of $\overline{q'^2}$. In the same manner as the case of the mean velocity profile⁽¹⁾, the introduction of a streamwise length scale $[h(h/\delta_0)C_{D_T}]$ can make the data of E and $(\overline{q'^2})_{peak}$ approximately to fall onto a single curve respectively for rectangular cylinders lower than $h/\delta_0 = 0.25$. It is also interesting to note that the decay of the turbulent kinetic energy is most rapid in the case of $h/\delta_0 = 0.375$. Figures 6(a)-(d) may suggest that the profile of $\overline{q'^2}$ becomes similar in the outer part of the disturbed boundary layers if an appropriate normalization is employed. The turbulent energy is then plotted in Fig. 8 in the form of $\overline{q'^2}/(\overline{q'^2})_{peak}$ versus $(y - y_p)/\delta$, where y_p is the coordinate of the maximum value of $\overline{q'^2}$. In the region

Fig. 5 Typical distributions of turbulent intensities and Reynolds shear stresses behind a rectangular cylinder.

far downstream of the cylinder where distinct maximum of $\bar{q}^2$ is not observed, y_p is tentatively defined as the location of the lower limit of the wake region of the boundary layer, $(\bar{q}^2)_{peak}$ being taken as the value of $\bar{q}^2$ at this location. The

(a) $h/\delta_0 = 0.125$

(b) $h/\delta_0 = 0.188$

(c) $h/\delta_0 = 0.250$

(d) $h/\delta_0 = 0.375$

Fig. 6 Distribution of turbulent kinetic energies $\bar{q}^2$ across relaxing boundary layers.

turbulent kinetic energy in the outer part of the relaxing boundary layers is thus found to be expressed by an empirical formula;

$$\left. \begin{aligned} \bar{q}^2/(\bar{q}^2)_{peak} &= 0.5\{1 - \text{erf}(\zeta)\} \\ \zeta &= 5.0(Y_w - 0.37) \\ Y_w &= (y - y_p)/\delta \end{aligned} \right\} \dots\dots\dots (6)$$

The profiles of Reynolds shear stress $-\rho u'v'$ in the relaxing turbulent boundary layers are shown in Figs. 9(a) - (d). The Reynolds shear stress has a maximum at a certain distance from the wall just in a similar manner to the turbulent energy $\bar{q}^2$, the maximum value decaying rapidly in the downstream direction. In the region sufficiently downstream, the distribution of

Fig. 7 Decay of turbulent kinetic energy.

Fig. 8 Similarity of turbulent kinetic energy in outer part of relaxing boundary layers.

the Reynolds shear stresses becomes very similar to that found in equilibrium turbulent boundary layers. In passing it may be added that $-\overline{u'v'}/u_\tau^2 = 1.0$ is satisfied in the vicinity of the wall when x/h is large enough.

Fig. 9 Distribution of Reynolds shear stresses $-\overline{u'v'}$ across relaxing turbulent boundary layers

It is known that the ratio α_1 of the Reynolds shear stress to the turbulent kinetic energy takes a constant value of about 0.15 over most part of equilibrium turbulent boundary layers, and this fact has been utilized in a calculation scheme of turbulent boundary layers⁽¹²⁾. It is clear from Fig. 10, however, that the ratio α_1 does not take a constant value in the relaxing nonequilibrium turbulent boundary layers considered here. Accordingly, such a calculation scheme cannot accurately predict the development of the relaxing turbulent boundary layers.

Fig. 10 Distribution of $-\overline{u'v'}/q^2$ across relaxing turbulent boundary layers.

3.3. Probability density

The probability density distribution of perfectly random motions is known to be Gaussian. Although the turbulent motions may seem to be irregular, their probability density is not exactly Gaussian. However, it is useful to compare the probability density distribution $P(u')$ of turbulence with the Gaussian distribution in order to demonstrate some fundamental properties of the turbulent velocity fluctuation. For the purpose of this comparison, it is customary to employ the third and fourth moment of $P(u')$ defined by

$$S = \left[\int_{-\infty}^{\infty} u'^3 P(u') du' \right] / \sigma^3 \quad (7)$$

$$F = \left[\int_{-\infty}^{\infty} u'^4 P(u') du' \right] / \sigma^4 \quad (8)$$

Here S is called the skewness and it measures the degree of asymmetry of $P(u')$ while F is called the flatness factor which measures the kurtosis of $P(u')$. The square root of the second moment, σ , is the familiar standard deviation, i.e. rms amplitude of the fluctuating velocity. Figure 11 shows the probability density distributions at several typical positions in the relaxing turbulent boundary layers. Although as will be observed in Fig. 11, the probability density distributions in the inner region of the boundary layer are approximately Gaussian ($S = 0$, $F = 3.0$), those in the outer layer are considerably different from Gaussian.

It may be noted that some nature of the wave form of the fluctuating velocity can be understood by the factors S and F (see Ref. (15)). Distributions of S and F in the relaxing boundary layers are shown in Fig. 12.

3.4. Energy spectrum and correlation function

Since the spectral distribution and the correlation function of the fluctuating velocity are directly related to the scale of the fluctuations, they are valuable sources of information on the mechanism of generation and dissipation of turbulent energy. Figure 13 shows the spectra at a few positions in the relaxing turbulent boundary layers.

It has been shown in §3.2 that the distributions of q^2 and $u'v'$ are much different from those in the equilibrium turbulent boundary layers, the effect of the disturbances caused by the cylinders remaining in the region considerably downstream of the cylinder. However, since the energy spectra compiled in Fig. 13

Fig. 11 Probability density distribution of longitudinal fluctuating velocities (solid lines imply the Gaussian distribution of the same standard deviations).

Fig. 12 Distribution of skewness S and flatness factors F across relaxing turbulent boundary layer.

are similar to those of equilibrium turbulent boundary layers, including the range of $-5/3$ and -7 power laws, it may be said that the characteristics of turbulence in wavenumber space (spectral space) are not much different between the two cases, i.e. relaxing and equilibrium turbulent boundary layers. Disturbances caused by the cylinder manifest themselves as a widening of the inertial subrange to the region of lower wavenumbers as compared with the case of equilibrium turbulent boundary layers (5). Namely, the wavenumber range where the $-5/3$ power-law spectrum is observed is $50 \text{ m}^{-1} < \kappa < 500 \text{ m}^{-1}$ at $y/\delta = 0.58$ and 0.8 in an equilibrium layer while the range becomes $30 \text{ m}^{-1} < \kappa < 600 \text{ m}^{-1}$ in the relaxing layer. Wide wavenumber range of $-5/3$ power-law spectrum is observed in high Reynolds-number turbulence such as atmospheric and oceanographic turbulences. Accordingly, it may be suggested that the relaxing turbulent boundary layers can be used as a model of atmospheric turbulent boundary layers during strong winds.

Since Fig. 13 indicates that there exists a rather wide range of wavenumbers where the local isotropy of turbulence is realized, it is possible to estimate the rate of viscous energy dissipation based on the hypothesis of the local isotropy, which is one of the most important parameters in small-scale turbulent motions. The rate of dissipation ϵ is defined by

$$\epsilon = \int_0^\infty D(\kappa) d\kappa = 1.5 \nu \int_0^\infty \kappa^2 E(\kappa) d\kappa = 1.5 \nu (\bar{u}'^2 / \lambda^2) \dots \dots \dots (9)$$

Fig. 13 Energy spectra in relaxing turbulent boundary layer.

where $D(\kappa)$ and $\kappa^2 E(\kappa)$ are the dissipation spectra and λ designates the Taylor microscale. The Kolmogorov microscale η_c is given by $\eta_c = (\nu^3/\epsilon)^{1/4}$ and the corresponding velocity scale by $v_c = (\epsilon\nu)^{1/4}$. The scales η_c and v_c can easily be determined once ϵ is known. Figure 14 shows the distributions of ϵ in the equilibrium and relaxing boundary layers, which are calculated from Eq.(9). It is observed that ϵ in the undisturbed boundary layer agrees fairly well with the result of Klebanoff⁽⁵⁾. The rate of energy dissipation is generally larger in the relaxing boundary layer than in the equilibrium one, being extremely large at the station $x/h = 32$ where the disturbances caused by the cylinder are still very large.

The scale of large eddies in boundary layers can be estimated from the autocorrelation function of the velocity fluctuation. The autocorrelation function $R(\tau)$ is defined by

$$R(\tau) = \left[\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T u'(t)u'(t+\tau) dt \right] / \bar{u'^2}$$

If Taylor's hypothesis is employed, the length scale of large eddies L_x is given by

$$L_x = U^* \int_0^\infty R(\tau) d\tau \quad \dots\dots\dots (10)$$

Since the correlation function and the energy spectrum constitute the Fourier transform pair, L_x can also be determined from the relation $L_x = U^* E(n)_{n=0} / 4.0$. The length scale thus obtained is in agreement with that calculated from Eq.(10) with an error of 8 percent at most. It should be mentioned that the phase velocity U^* in Eq.(10) has been replaced by the local mean velocity U in the calculation of L_x . The autocorrelation function at several

Fig. 14 Distribution of the rates of dissipation ϵ across relaxing turbulent boundary layers.

positions in the relaxing turbulent boundary layers is shown in Fig. 15. The length scale determined from Eq.(10) corresponds to a wave length in the range of $-5/3$ power-law spectrum so that L_x may be considered to represent the scale of large isotropic turbulent eddies. The length scale L_x is not the scale of largest eddies in the boundary layer, the largest scale being of the order of the boundary-layer thickness.

Three length scales λ , η_c and L_x in the relaxing turbulent boundary layers are summarized in Fig. 16. The ratio of the integral scale L_x to the boundary-layer thickness δ is about 0.4 and this value agrees with that in the equilibrium boundary layers. The ratio between the Kolmogorov microscale η_c and the Taylor microscale λ is found to be about 26.

4. Conclusions

In order to clarify the characteristics of turbulence in relaxing boundary layers behind several two-dimensional rectangular cylinders attached to a plane wall, detailed measurements were made of turbulent kinetic energy, Reynolds shear stress, probability density, power spectrum, intermittency factor, correlation function and length

Fig.15 Autocorrelation function of longitudinal fluctuating velocity.

Fig. 16 Distribution of various length scales in relaxing turbulent boundary layers (symbols as in Fig. 14).

scale of turbulent eddies. The main results of the present investigation may be summarized as follows:

- (1) The turbulent kinetic energy $\overline{q^2}$ and the Reynolds shear stress $-\rho \overline{u'v'}$ in the relaxing boundary layers are much larger than those in equilibrium boundary layers, and have a distinct maximum at a certain normal distance from the wall.
- (2) If an appropriate scaling is made, the distribution of $\overline{q^2}$ in the outer part of the boundary layers shows a selfpreserving form regardless of the magnitude of disturbances.
- (3) The process of decay of the turbulent energy behind rectangular cylinders can approximately be made to fall onto a single curve for $h/\delta_0 \leq 0.25$ by the introduction of the longitudinal length scale $[h(h/\delta_0)C_{D_T}]$.
- (4) In the relaxing boundary layers, the $-5/3$ power-law spectrum is observed in a wider range of wavenumbers as compared with the case of the equilibrium boundary layers, the widening of this spectrum to lower wavenumbers being significant.
- (5) The width of the intermittently turbulent region in the relaxing boundary layers is larger than that in the equilibrium ones. The roughness of the superlayer is found to be also larger.

The authors express their sincere thanks to Mr. H. Tamura for his helpful discussions and also wish to thank Mr. T. Yamazaki and Mr. T. Sampo for their skillful assistance in constructing the experimental apparatus.

References

- (1) Suzuki, Y., et.al., Bulletin of the JSME, 21-159(1978),1332.
- (2) Bradshaw, P. and Wong, F.Y.F., J.Fluid Mech., 52-1(1972),113.
- (3) Corrsin, S. and Kistler, A.L., NACA TN, 1244(1955).
- (4) Townsend, A.A., Aust. J. Sci. Res., Ser. A, 2(1949),451.
- (5) Klebanoff, P.S., NACA TN., 1247(1955).
- (6) Fiedler, H. and Head, H.R., J. Fluid Mech., 25(1966),719.
- (7) Kovasznay, L.S.G., et al., J. Fluid Mech., 41-2(1970),283.
- (8) Townsend, A.A., J. Fluid Mech., 41-1(1970), 13.
- (9) Wygnanski, I. and Fiedler, H.E., J. Fluid Mech., 41-2(1970),327.
- (10) Bradshaw, P., et al., J.Fluid Mech., 28-3(1967),593.
- (11) Arie, M. and Rouse, H., J.Fluid Mech., 1-2(1956),129.
- (12) Bradshaw, P., *An Introduction to Turbulence and Its Measurement*, (1971), Pergamon Press.
- (13) Lumley, J.L. and Panofsky, H.A., *The Structure of Atmospheric Turbulence*, (1964), John Wiley and Sons.
- (14) Grant, H.L., et al., J. Fluid Mech., 12(1962),241.
- (15) Tennekes, H. and Lumley, J.L., *A First Course in Turbulence*, (1972), MIT Press.