The Structure of a Turbulent Wake behind

a Cruciform Circular Cylinder*

(2nd Report, The Streamwise Development of turbulent flow field)

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Detailed measurements of the turbulent quantities such as the turbulent intensity components and Reynolds shear stress in the cruciform circular cylinder wake have been made, in order to examine the similarity profile of the turbulent quantities and the streamwise growth of the turbulent flow field. Experimental results are summarized as follows: For the far downstream region, the decay rate of turbulent velocity scales is close to that of the mean velocity scale, and the profiles of three-components of turbulent intensity and Reynolds shear stress are similar. In the vicinity of a corner, a distortion due to secondary flows is observed on the contours of the turbulent quantities. Reynolds number based on the velocity scale U_{d0} and the length scale L_x is constant and therefore the present turbulent wake remains steady.

Key Words: Turbulence, Cruciform Circular Cylinder, Turbulent Wake, Turbulent Intensity, Reynolds Stress, Characteristic Scales, Self-Preservation

1. Introduction

In the previous paper⁽¹⁾, the authors stated that in the mean velocity field of a turbulent wake behind a cruciform circular cylinder which was composed of two sufficiently long circular cylinders, the contours of the mean velocity maintain a crisscross shape even in the far downstream region and secondary flows developed in the center region of the present wake, and furthermore that the scales of the flow field were different from those in the two-dimensional and the axisymmetric wake.

In engineering, the flow fields closely related to the present wake often appear, such as the diffusion problems⁽²⁾ of a corpuscle and a thermal exhaust in the rear region of the frame structure and the effects⁽³⁾ on a fish farming and a fish gathering with respect to the artificial reef. In such cases the information on the turbulent quantities is necessary in addition to that on the mean flow properties. Especially, the detailed measurements are required in the center region of the turbulent field behind a cruciform cylinder to investigate the three-dimensionality based on the interference due to the both cylinder wakes.

The three-dimensional wakes⁽⁴⁾⁽⁵⁾ studied

so far are approximate to the axisymmetric wake and thus are limited to those cases of deterioration in the far downstream field. On the other hand, the present turbulent wake remains steady downstream and therefore the Reynolds number based on the appropriate scales of both velocity and length is constant.

From these points of view, we intended to clarify the feature of the turbulent field and the downstream development of flow field for the present wake behind a cruciform circular cylinder in detail. In this paper, the relation between the streamwise variation of each turbulent quantity in the cross section and that of the mean velocity field, the similarity of each turbulent property and the downstream variation of both various turbulent parameters and scales are investigated.

Main nomenclature used are the same as in the 1st report. The new notations are given in the following.

(x, y', z') : Cartesian coordinate system
rotated clockwise by 45 degrees
with respect to x axis

U_1 : free stream velocity

U_{d0} : mean velocity defect on the x
axis (maximum velocity defect)

U, V', W' : mean velocity components in the
x, y' and z' directions,
respectively

u, v', w' : fluctuating velocity components
in the x, y' and z' directions,
respectively

u, v, w : fluctuating velocity components
in the x, y and z directions,
respectively

$(1/2)\overline{q^2}$: turbulent kinetic energy
[Eq.(1)]

u^*, l^* : velocity scale and length scale
[Eqs.(3),(4)]

ν_T : eddy viscosity [Eqs.(2),(5)]

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- l : mixing length [Eq.(6)]
 R_T : turbulent Reynolds number [Eq.(7)]
 L_x : integral length scale determined from the auto-correlation of $u(t)$ [Eq.(10)]
 R_L : Reynolds number [Eq.(11)]
 λ : Taylor's micro scale [Eq.(12)]
 l_e : Kolmogorov's length scale [Eq.(13)]

Subscripts

- rms : rms value
 c : on the wake center axis (x-axis)
 y, y' : on the y axis (z=0 plane) and the y' axis (y=z plane), respectively

2. Experimental Apparatus and Techniques

Measuring equipment, experimental Reynolds number and measuring range were the same as those in the previous paper⁽¹⁾. For the measurement of fluctuating velocity, an ordinary constant temperature hot wire anemometer with x-wire probe (5 μ m diameter and 1 mm effective length) was used. Two hot wires of x probe were kept at an angle of 45 degrees to the free stream and also a plane which contained two wire was set up to coincide with x-y plane and x-y' plane in any case respectively. The anemometer outputs were processed by the sum-difference-multiplication unit and then by the rms analyser and the integrator with integration time of 23 s. For the auto-correlation measurement a u-fluctuating signal was directly given to a digital correlator with sampling time of 100 μ s and was estimated as an averaged value of about 10 to 30 s and this output was recorded on an X-Y recorder. Furthermore, the dissipation rate was evaluated from $\partial u/\partial t$ which was determined with the differentiating circuits with frequency response of 4 kHz, under the assumption of Taylor's hypothesis.

3. Experimental Results and Discussion

Since the present flow field was fairly complicated, at first the overall feature of the turbulent field was investigated and subsequently the similarity of the flow field was examined.

Fig.1 Contours of the turbulent kinetic energy (x/d = 30.5)

3.1 Turbulent Kinetic Energy Distribution and its Streamwise Development

In the turbulent field behind a cruciform cylinder, the turbulent kinetic energy described below was examined,

$$\frac{1}{2} \overline{q^2} = \frac{1}{2} (\overline{u^2} + \overline{v^2} + \overline{w^2}) \dots \dots \dots (1)$$

Fig.1 shows the contours of the turbulent kinetic energy $(1/2)\overline{q^2}$ in the y-z plane at $x/d = 30.5$. These results were obtained from the measurements at about 900 points in the cross section. This profile indicates a symmetric crisscross shape and in the center region of the present wake the turbulent kinetic energy does not increase in magnitude exceptionally. In the region along two cylinders the contours of turbulent energy are parallel to both cylinder-axes in the range of $|y/d|, |z/d| \geq 10$, hence the flow field approximates to a two-dimensional wake. On the other hand, near the wake center the contours of the turbulent energy show a large variation and the value of $(1/2)\overline{q^2}$ is lower than that of the region around the wake center. It is considered that these changes of the contours occurring in the center region depend on the secondary currents which distort the isovels towards the wake center in the corner region of the present wake. The variation of $(1/2)\overline{q^2}$ near the wake center is extremely small, and its value is still

Fig.2 Streamwise variation of the turbulent kinetic energy profile (left hand side: y = z plane, right hand side: z = 0 plane)

Fig.3 Streamwise variation of the turbulent intensity at the wake center

low even in the far downstream section of $x/d = 298.5$ not shown in the figure.

The streamwise variation of the turbulent kinetic energy profile for both the $y=z$ plane (left hand side) and the $z=0$ plane (right hand side) is shown in Fig.2. Turbulent kinetic energy profile on the $z=0$ plane shows a fairly large change and has a constant value in the range of $y/d \geq 15$. As the flow field goes downstream, this variation of profile gradually decreases and the profile approaches a monotonous shape that shows the minimum value at the wake center in the far downstream region. On the other hand, the turbulent kinetic energy profiles on the $y=z$ plane are similar to those of both the two-dimensional and the axisymmetric wakes which have a maximum value at any position away from the wake center axis in all sections, in spite of the interference due to the two cylinders wake. However, it can be considered that these profiles show a considerably large variation across the flow field since the spanwise position which takes a maximum value of $(1/2)\overline{q^2}$ moves from the $z=0$ plane to the $y=z$ plane in the region of $x/d = 30.5$ to 90.5 . This spanwise variation was also found for the mean velocity field (see Fig.5 in 1st Rep.).

As the self-preservation of the mean velocity field was confirmed in the previous paper, the existence of the self-preservation for the turbulent field will be also expected. Let's examine the downstream devel-

opment of the turbulent field by using the streamwise variation of $\sqrt{\overline{q^2}}/U_1^{1/6}$ at the wake center which is regarded as the characteristic velocity scale. The result is shown in Fig.3. From this result, it is clear that the decay rate of this scale depends on the streamwise region. $(\sqrt{\overline{q^2}})_c/U_1$ decays as $x^{-0.67}$ in the range of $x/d \leq 298.5$ and this decay rate is the same value as that of the rectangular jet⁽⁷⁾, whereas in the far downstream region the velocity scale decays as $x^{-0.38}$ and is almost similar to that of the mean flow field ($U_{d0} \propto x^{-0.37}$). These trends are different from that of the mean velocity field and this is common to almost all turbulent flows and it means that the response of the turbulent field is slower than that of the mean field.

3.2 Contours of the Turbulent Intensity

In order to examine the overall feature of the turbulent field and the correspondence with the mean field, contours of the turbulent intensity profiles at $x/d = 30.5$ and 298.5 are shown in Fig.4(a),(b) and Fig.5(a),(b) respectively. These results were obtained through the measurements at many points in the cross section. The profile of w_{rms}/U_1 is not shown, since the symmetry of the profile between v_{rms}/U_1 and w_{rms}/U_1 with respect to the $y=z$ plane is good.

At the section of $x/d = 30.5$, the whole

(a) u_{rms}/U_1

(b) v_{rms}/U_1

Fig.4 Contours of the turbulent intensity components ($x/d = 30.5$)

(a) u_{rms}/U_1

(b) v_{rms}/U_1

Fig.5 Contours of the turbulent intensity components ($x/d = 298.5$)

aspect of both profiles of u_{rms}/U_1 and v_{rms}/U_1 shows a symmetric crisscross shape and contours of these turbulent intensities in the corner region of the present wake distort towards the wake center due to the secondary currents, which agrees with the feature found in the isovels. The characteristic feature of the present turbulent field appears clearly at the center region of the wake. The value of u_{rms}/U_1 becomes maximum in the shadowed portion in the figure at $x/d = 30.5$ and this region shows a crisscross shape which extends to the so called eye of isovels (see Fig.5 in the previous paper⁽¹⁾). However, the value of contours that show a circle is comparatively low in the region near the wake center. This trend corresponds to the magnitude of the velocity gradient conjectured from the isovels. On the other hand, the value of v_{rms}/U_1 increases with an increasing z/d along the z axis but the variation along the y axis is lesser. The position of contours of $v_{rms}/U_1 = 0.08$ near the wake center corresponds to the region that has a small velocity defect on the cylinder axis described in the previous paper.

At the section of $x/d = 298.5$, both profiles of u_{rms}/U_1 and v_{rms}/U_1 still maintain the crisscross shape and their magnitudes are fairly small and the distortion of the contours due to the secondary currents does not appear clearly. The profile of u_{rms}/U_1 has four belt-shaped regions which extend towards both cylinder axes (inner region encircled with the dotted line where the turbulent intensity takes a large value). In the inner region described above, there exist eight portions where u_{rms}/U_1 has the maximum value at symmetric locations with respect to both y' axis and z' axis. These regions correspond to the portions where the Reynolds shear stresses $-\overline{uv}$ and $-\overline{uw}$ have large values and it is expected that in these regions the

production of the turbulent kinetic energy is also large. The contours of v_{rms}/U_1 take a large value at the same locations as that of u_{rms}/U_1 .

3.3 Reynolds Shear Stress Profile

The Reynolds shear stress shows a complicated three-dimensional profile. At first the isometric projections of $-\overline{uv}/U_1^2$ for the quadrant section at $x/d = 30.5$ and 298.5 are shown in Figs.6 and 7 respectively. At the section of $x/d = 30.5$, the maximum value in each slice of z/d is minimum at $z/d = 0$ and maximum at $z/d = 2$. The shapes of profiles are similar in the region of $z/d \geq 12$ and they gradually approach a two-dimensional profile as z/d increases. In the region of $z/d \leq 2$, the profile has a positive maximum value near the wake center and then takes a negative minimum value according to the spanwise variation of the mean velocity gradient. In the far downstream region of $x/d = 298.5$, the magnitude of the Reynolds shear stress rapidly decreases to one-tenth at $x/d = 30.5$ and this decrease is remarkable at the center region. This trend corresponds to that of the turbulent intensity. The location of z/d where $-\overline{uv}/U_1^2$ takes the maximum value shifts from $z/d = 2$ at $x/d = 30.5$ to $z/d = 8$ at $x/d = 298.5$, owing to the development of a turbulent field.

The expression for the Reynolds shear stress using the eddy viscosity can be given by Eq.(2), because of the establishment of

Fig.6 Isometric projection of the Reynolds shear stress $-\overline{uv}/U_1^2$ ($x/d = 30.5$)

Fig.7 Isometric projection of the Reynolds shear stress $-\overline{uv}/U_1^2$ ($x/d = 298.5$)

Fig.8 Contours of the Reynolds shear stress $-\overline{uv}/U_1^2$ ($x/d = 298.5$)

Fig.9 Stress vectors based on the Reynolds shear stress ($x/d = 298.5$)

the ordinary thin-shear layer approximation in the present experiment,

$$\left. \begin{aligned} -\overline{uv} &= v_T \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \doteq v_T \frac{\partial U}{\partial y} \\ -\overline{uw} &= v_T \left(\frac{\partial U}{\partial z} + \frac{\partial W}{\partial x} \right) \doteq v_T \frac{\partial U}{\partial z} \end{aligned} \right\} \dots\dots\dots (2)$$

Let's explain the profile of the Reynolds shear stress under this assumption. Fig.8 shows the contours of $-\overline{uv}/U_1^2$ at $x/d = 298.5$. The profile of $-\overline{uw}/U_1^2$ is not shown because of the fine symmetry of the profile between $-\overline{uv}/U_1^2$ and $-\overline{uw}/U_1^2$ with respect to the $y = z$ plane. The value of $-\overline{uv}/U_1^2$ becomes small, as the mean velocity gradient $\partial U/\partial y$ decreases at the vicinity of y axis and the contours of the Reynolds shear stress have a constriction at those portions.

Let's examine the stress vector $(-\overline{uv}, -\overline{uw})$ due to the Reynolds shear stress acting on the unit area of $y-z$ plane. As the velocity gradient vector $(\partial U/\partial y, \partial U/\partial z)$ intersects at right angles to the isovels, the Reynolds shear stress vector can be also expected to have a similar relation to that of the velocity gradient vector under the assumption of a constant value of v_T . Fig.9 shows the stress vectors in addition to the isovels and this result supports the conjecture described above very well. Therefore, although the present wake clearly shows a three-dimensionality, the gradient-diffusion type model might be applied to the present turbulent field in the same way as the square jet⁽¹⁰⁾. This figure also shows that $y = z$

plane is a symmetric plane for the Reynolds shear stress.

3.4 Similarity Profiles of Turbulent Quantities

In general, it is difficult to examine the self-preservation for the entire region of a three-dimensional flow field, but it can be expected from the self-preservation of the mean velocity profile found in the previous paper⁽¹⁾ that at least there exists the self-preservation of the turbulent quantity for the typical symmetric plane, that is, the similarity profile as $u_{rms}/U_0 = f(y'/b_{y'})$ for the u fluctuating component. Let's examine the similarity of turbulent quantities on both symmetric planes of $y = z$ plane and $z = 0$ plane. Here, turbulent quantities on $y = z$ plane were measured by arranging the x -array plane of the x -wire into $x-y'$ plane or $x-z'$ plane, taking account of the result shown in Fig.9. Then, the profiles are non-dimensionalized by using the maximum velocity defect U_0 and the characteristic length scales $b_{y'}$ and l_y for each symmetric plane, where $b_{y'}$ is half-width for $y = z$ plane and l_y is Townsend's length scale for $z = 0$ plane. The streamwise variation of these scales was discussed in the previous paper⁽¹⁾.

Figs.10(a) to (c) show the profiles of turbulent intensity components for both symmetric planes, including the similarity profiles of the two-dimensional wakes by Townsend⁽¹¹⁾ and authors⁽¹²⁾ and those of the axisymmetric wake by Chevray⁽¹³⁾. In these figures, the spanwise profile is drawn on $z = 0$ plane and the lateral profile on $y = z$ plane respectively for the two-dimensional wake. The slight difference between the result by Townsend and that by authors is discussed in ref.(12).

As to the profiles on $z = 0$ plane, at $x/d = 30.5$ profiles of turbulent intensity components are different from one another but the magnitudes of these profiles are almost the same order at the wake center. The value of w_{rms}/U_0 becomes fairly large compared with those of u_{rms}/U_0 and v_{rms}/U_0 in the region far from the wake center. The locations where u_{rms}/U_0 takes the maximum value and the minimum value respectively correspond to those where U_d/U_0 takes the minimum value and the maximum value respectively. In the downstream field, the profiles of turbulent intensity components become gentle and take a slightly small value near the wake center and a constant value in the region of $y/l_y \geq 1$. In the region beyond $x/d = 298.5$, the profiles of u_{rms}/U_0 , v_{rms}/U_0 and w_{rms}/U_0 become similar. Here, the magnitude of these profiles in the region of large value of y/l_y is different from that of the two-dimensional wake

Fig.10 Similarity of the profiles of the turbulent intensity component (left hand side: $y = z$ plane, right hand side: $z = 0$ plane)

obtained by authors, because the characteristic velocity scale U_{d0} used in the non-dimensionalization is larger than that of the two-dimensional wake.

On the other hand, on the profile for $y = z$ plane, profiles of turbulent intensity components are different from one another until $x/d = 90.5$, but they have a common similar shape which takes the minimum value at the wake center and also the maximum one at $y'/b_y \approx 0.9$ farther downstream. These profiles are similar in the region beyond $x/d = 298.5$, but they have different shapes and smaller values, comparing with those of the two-dimensional and the axisymmetric wakes. In the similarity region of $x/d \geq 298.5$, the magnitude of turbulent intensity components has almost the same relation $u_{rms} > v_{rms}$ ($v_{rms} \approx w_{rms}$) as the result of the two-dimensional wake by authors. It can be considered from the results described above that the turbulent intensity profiles become approximately similar in the entire cross section at constant x in the region of $x/d \geq 298.5$.

In the next place, let's consider the Reynolds shear stress profile. The results for $y = z$ plane and $z = 0$ plane are shown in Figs. 11 and 12 respectively, including the similarity profiles of the two-dimensional wakes by Townsend⁽¹⁴⁾, Narasimha et al.⁽¹⁵⁾ and authors⁽¹²⁾ and those of the axisymmetric wake by Chevray⁽¹³⁾. The value of $-\overline{uv}/U_{d0}^2$ is extremely large and close to that of the

two-dimensional wakes at the section of $x/d = 30.5$, but this value rapidly decreases as x/d increases and then a similarity profile which takes the maximum value at $y'/b_y \approx 0.9$ is obtained in the region of $x/d \geq 211$. This result is extremely small compared with that of the two-dimensional wake because the characteristic velocity scale U_{d0} which is used in the non-dimensionalization is considerably larger than that of the two-dimensional wake.

On the other hand, the profiles of $-\overline{uv}/U_{d0}^2$ on $z = 0$ plane, show a fairly large variation with the positive maximum value and the negative minimum one and their magnitude is small compared with that of $y = z$ plane in the region until $x/d = 90.5$. In the downstream region it is not clear whether the profiles of $-\overline{uv}/U_{d0}^2$ become similar, because the values of the Reynolds shear stress are extremely small. However, these profiles seem to be able to be approximated to one curve in the region of $x/d \geq 211$. Therefore, the similarity of the Reynolds shear stress profile in the entire cross section at constant x can be also expected as well as that of the turbulent intensity profile.

3.5 Turbulent Parameters and Scales

At first, let's examine the characteristic scale of turbulent flowfield described by using the Reynolds shear stress because the turbulent field becomes similar in the far downstream region. Fig. 13 shows the velocity and the length scales for $y = z$ plane (y' axis) and $z = 0$ plane (y axis), proposed by Tennekes-Lumley⁽⁸⁾ and described as follows;

$$u^* = (\max |-\overline{uv}|)^{1/2}, \dots\dots\dots (3)$$

$$l^* = U_{d0} e^{-1/2} / \max |\partial U / \partial y| \dots\dots\dots (4)$$

Both velocity scales of u_y^* for y axis and $u_{y'}^*$ for y' axis, exhibit almost the same decay rate as $(\sqrt{q^2})_c$. In other words, they have a transitional tendency of the decay rate and then coincide with that of the self-preserving state. The length scales of l_y^* and $l_{y'}^*$ take the same tendency of the streamwise variation as those of l_y and $l_{y'}$ defined by Townsend⁽¹⁶⁾ respectively.

Fig. 11 Similarity of the profile of the Reynolds shear stress $-\overline{uv}/U_{d0}^2$ ($y = z$ plane)

Fig. 12 Similarity of the profile of the Reynolds shear stress $-\overline{uv}/U_{d0}^2$ ($z = 0$ plane)

Fig. 13 Streamwise variation of the velocity and the length scales for the turbulent flow field defined by Tennekes-Lumley

The non-dimensional profiles of the eddy viscosity ν_T and the mixing length ℓ defined in the following equations for $y=z$ plane are shown in Fig.14,

$$-\overline{uv} = \nu_T \left(\frac{\partial U}{\partial y} \right), \dots\dots\dots (5)$$

$$-\overline{uv} = \ell^2 \left| \frac{\partial U}{\partial y} \right| \left(\frac{\partial U}{\partial y} \right), \dots\dots\dots (6)$$

Both profiles become similar in the region of $x/d \geq 211$ and take a constant value in the whole range of the present wake except the center region and the outer edge region. The values of $\ell/b_{y'}$ and $\nu_T/U_{d0} b_{y'}$ at this location are about 0.23 and 0.037 respectively and are extremely small compared with those of the two-dimensional wake⁽¹²⁾ ($\nu_T/U_{d2} b_2 = 0.081$, $\ell/b_2 = 0.35$).

The turbulent Reynolds number defined appropriately is an important parameter to predict the developing process of various turbulent flows and to distinguish the characteristics of the flow field. The turbulent Reynolds number defined by the following equation for the present wake is shown in Fig.15,

$$R_T = U_{d0} b_{y'} / \nu_T, \dots\dots\dots (7)$$

The value of R_T takes a constant value of about 27.4 in the region beyond $x/d = 211$. The value of R_T for the two-dimensional wake is expressed as 12.5 by Townsend¹⁶, 15.4 by Narasimha et al⁽¹⁵⁾ and 12.4 by authors⁽¹²⁾, whereas the value of R_T is given as 14.1 for the axisymmetric wake⁽⁸⁾. Therefore, the value of R_T for the present wake is fairly large compared with those of the two-dimensional and the axisymmetric wakes. The difference of R_T may be explained by the fact that the eddy viscosity for the present wake is small and Reynolds shear stress is small compared with other kinds of wakes.

In the equilibrium boundary layer⁽¹⁷⁾, the following relation between the turbulent kinetic energy and the turbulent shear stress is approximately satisfied,

$$a_1 = \tau / \rho q^2 = 0.15, \dots\dots\dots (8)$$

Fig.14 Profiles of eddy viscosity and mixing length for the $y=z$ plane

Fig.15 Turbulent Reynolds number

In addition, the value of $a_1 = 0.15$ is also reported for the wake and the jet. Fig.16 shows the following equation for $y=z$ plane,

$$a_1 = -\overline{uv} / (\overline{u^2} + \overline{v^2} + \overline{w^2}), \dots\dots\dots (9)$$

The value of a_1 seems to take a constant value of about 0.16 within the experimental uncertainty in a fairly wide range except for near the wake center and the outer edge of the wake.

In the next place, let's examine the streamwise variation of the turbulent eddy scales closely related to the turbulent energy spectrum. The integral length scale L_x , Taylor's micro scale λ and Kolmogorov's length scale ℓ_c are well known as the typical turbulent scales. The integral length scale L_x can be obtained from the auto-correlation function of the x component fluctuating velocity $u(t)$ by applying Taylor's hypothesis using the following equation (10),

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

where, U is the local mean velocity. The streamwise variation of L_x at the location of the wake center axis may be considered to indicate the downstream development of the characteristic length scale for the present wake as shown in Fig.17. L_x increases as $x^{0.37}$ in the present wake and this result shows the feature of the streamwise development for the cruciform cylinder wake. Here, L_x is considered a large eddy scale extracting the turbulent kinetic energy from the mean flow. We define a new Reynolds number based on the velocity defect U_{d0} and the integral length scale L_x at the location of the wake center axis,

$$R_L = U_{d0} L_x / \nu, \dots\dots\dots (11)$$

It is clear that the relation of $R_L = \text{const.}$

Fig.16 Profile of a_1 for the $y=z$ plane

Fig.17 Streamwise variation of L_x , λ and ℓ_c

is established from the consideration of the powers of U_0 and L_x . This result means that the present cruciform cylinder wake remains steady downstream as well as the two-dimensional wake. Taylor's micro scale λ corresponds to the eddy scale in the inertial subrange of the turbulent energy spectrum, that is, in the equilibrium state for the cascade process of turbulence. Meanwhile Kolmogorov's length scale l_ϵ indicates the scale of the smallest eddy dissipating into the heat. λ and l_ϵ are closely related with the dissipation rate ϵ and defined as follows respectively,

$$\lambda = \left(\frac{15 \overline{vu^2}}{\epsilon} \right)^{1/2}, \dots\dots\dots (12)$$

$$l_\epsilon = \left(\frac{\nu^3}{\epsilon} \right)^{1/4}, \dots\dots\dots (13)$$

where ϵ is obtained from the relation $\epsilon = 15\nu (\partial u / \partial t)^2 / U^2$ by applying Taylor's hypothesis. The profiles of λ and l_ϵ are shown in Fig.17, including the profile of L_x . The ratio of l_ϵ to λ is a magnitude of about 1/10. Both scales of l_ϵ and λ increase as about $x^{0.5}$ and this tendency agrees well with that of the two-dimensional wake. This result suggests that in a small scale structure of turbulence the difference of the development process between the present wake and the two-dimensional wake is small.

4. Conclusions

Turbulent quantities such as the turbulent intensity components and the Reynolds shear stress and various turbulent parameters were measured for a cruciform circular cylinder wake in detail. From the results the following were revealed.

- (1) Contours of turbulent quantities maintain a crisscross shape in the entire cross section towards downstream, but in the center region of the wake these profiles show a peculiar tendency. Near the wake center, turbulent quantities do not exceptionally increase in magnitude, conversely the values of these quantities become small compared with those in the region surrounding the wake center region. In the corner region of the contours of the turbulent quantities at the section of the upstream region, the same distortion of the isovalues due to the secondary currents is observed.
- (2) Turbulent quantity profiles for the $y=z$ plane and the $z=0$ plane become almost similar in the region beyond about $x/d = 300$. In this region it may be considered that the turbulent flow field becomes approximately similar in the entire region at constant x , analogous to the mean flow field.

- (3) In the self-preserving region of $x/d \geq 300$, the velocity scales closely related to the streamwise development of the turbulent flow field decay as about $x^{-0.4}$ in accordance with the decay rate of the velocity scale U_0 for the mean flow field. Meanwhile in a relatively upstream region there exists a range showing a transitional tendency of the decay rate.

- (4) The turbulent Reynolds number defined as $R_T = U_0 b y' / \nu_T$ takes a value of 27.4 which is considerably larger than those of the two-dimensional and the axisymmetric wakes. Meanwhile, the local Reynolds number $R_L = U_0 L_x / \nu$ has a constant value in the streamwise direction, which means that the turbulent flow field of the cruciform circular cylinder wake remains steady towards downstream.

References

- (1) Osaka, H., et al., Bull. JSME, 26-213 (1983-3).
Trans. JSME (in Japanese), 48-431, B (1982), 1229.
- (2) Aynsley, R.M., et al., Architectural Aerodynamics, (1977), Applied Sci. Publ.
- (3) Osaka, H., et al., Fisheries Engineering (in Japanese), 15-1 (1978), 19.
- (4) Kuo, Y.H. and Baldwin, L.H., J. Fluid Mech., 27-2 (1967), 353.
- (5) Уханова, М.Н., Инженерно-физический журнал, 25-5 (1973), 893.
- (6) Schlichting, H., Boundary Layer Theory, (1979), 475, McGraw-Hill.
- (7) Trentacoste, N. and Sforza, P., AIAA J., 5-5 (1967), 885.
- (8) Tennekes, H. and Lumley, J.L., A First Course in Turbulence, (1972), MIT Press.
- (9) Bradshaw, P., Turbulence, (1978), 29, Springer-Verlag.
- (10) Nakamura, I., et al., Trans. JSME (in Japanese), 44-388 (1978), 4197.
- (11) For instance, Rotta, J.C., Turbulence (translated into Japanese by Ohji, M.), (1975), Iwanami Press.
- (12) Yamada, H., et al., Tech. Rep. Yamaguchi Univ., 2-4 (1980), 329.
- (13) Chevray, R., Trans. ASME, Ser. D, 90-2 (1968), 275.
- (14) For instance, Gartshore, I.S., J. Fluid Mech., 30-3 (1967), 547.
- (15) Narasimha, R. and Prabhu, A., J. Fluid Mech., 54-1 (1972), 1.
- (16) Townsend, A.A., The Structure of Turbulent Shear Flow, (1976), Cambridge Univ. Press.
- (17) Bradshaw, P., et al., J. Fluid Mech., 28-3 (1967), 593.
- (18) Harsha, P.T. and Lee, S.C., AIAA J., 8-8 (1970), 1508.