Experimental Study on a Three-Dimensional Wall Jet

(Flow Field in a Cross-Section of Developed Region)*

Yoshihiro INOUE**, Haruhisa YANO*** and Shintaro YAMASHITA**

**Faculty of Engineering, Gifu University,
1-1 Yanagido, Gifu-shi, Gifu 501-1193, Japan

E-mail: inouey@gifu-u.ac.jp

***Department of Mechanical Engineering, Daido Institute of Technology,
10-3 Takiharu-cho, Minami-ku, Nagoya, Aichi 457-8530, Japan

Abstract

This study is to clarify the flow structure of a three-dimensional wall jet discharged tangentially on a flat surface from a circular nozzle. Distributions of the mean velocities and fluctuating velocities in a cross section of a fully-developed flow region were measured by using a single hot-wire probe and cross-wire probes. It is confirmed in any position of the lateral direction that the distributions of the mean velocities U and W in the direction normal to the wall are made similar to each other when they are made dimensionless by the maximum local velocity while the jet height remains almost invariable in the spanwise direction. The direction of the mean flow vector in the inner layer is remained constant while the direction of the mean flow vector outside the half-value height is coincided with the direction of the jet axis. The distributions of the turbulent statistics in the direction normal to the wall are almost similar to each other outside the half-value height due to the scaling by the maximum local velocity, and on the other hand, the magnitude of the turbulent energy and Reynolds stress in the wall-side region becomes larger at the position farther from the jet axis.

Key words: Wall Jet, Three-Dimensional Flow, Turbulence, Secondary Flow

1. Introduction

The study of plane-wall jet, early originated in the experiment by Förthman and the similarity analysis by Glauert, is now evolved to the refinement of the method of numerical analysis (e.g., Ref. [1]). The wall jet is characterized by coexistence of large scale turbulence in a free jet and comparatively small-sized turbulence in a wall flow, and then the flow field is divided conventionally into two regions: the outer layer with large scale turbulence and the inner layer with smaller scale turbulence. However, according to the study of the present authors⁽²⁾, the large scale turbulence is still very dominant even in the near wall region; in particular, the spanwise structure is conspicuously different from the boundary layer flow. In three-dimensional wall jets, moreover, the secondary flows in the plane orthogonal to the main flow are superposed, and it is difficult to understand these flows only on the basis of the analogical inference from the conventional interpretation of the plane-wall jet.

In an effort to clarify the phenomena of three-dimensional wall jets, a great many studies have been so far made. Launder & Rodi presented prospective research papers⁽³⁾⁽⁴⁾ in the early 1980s, and Koso *et al.*⁽⁵⁾⁽⁶⁾, Fujisawa *et al.*⁽⁷⁾, Matsuda *et al.*⁽⁸⁾, Padmanabham *et*

*Received 30 Nov., 2007 (No. T1-06-0270)
Japanese Original : Trans. Jpn. Soc. Mech.
Eng., Vol.72, No.724, B (2006),
pp.2940-2947 (Received 20 Mar., 2006)
[DOI: 10.1299/jfst.2.655]

al.⁽⁹⁾, Sullivan *et al.*⁽¹⁰⁾ and Abrahamsson *et al.*⁽¹¹⁾ have conducted significant experiments. The results of these experiments have shown the process of the flow development and the existence of the region where the flow similarity is established, and furthermore pointed out the formation of the secondary flow as a cause of the anisotropic spread of the jet, and clarified the flow structure in the near exit field of the jet.

While the understanding on the phenomena of this flow is deepened by the experimental studies, a considerable progress has been made in regard to the numerical analysis. At the 6th ERCOFTAC/IAHR/COST Workshop on Refined Flow Modelling⁽¹⁾, comparison was made in turbulent models for the plane-wall jets and the three-dimensional wall jets. In this workshop, Craft and Obi took care of the three-dimensional wall jet, and showed the result gist of their work later⁽¹²⁾⁽¹³⁾. They emphasized in their research papers the difficulties of numerical analysis related to the anisotropic development of the flow field, and stated the necessity of research endeavors toward the further refinement of the models.

In consideration of the state of these researches, this study was made to investigate experimentally the mean and turbulent structure in order to build a more detailed experimental database related to the three-dimensional wall jet. The experiment was conducted in the flow field produced by a jet discharged tangentially on a flat plate from a circular nozzle, and done in particular at a representative cross section of $x/b_j = 60$ in fully developed region using hot-wire anemometry. On the basis of the measured results, the statistical quantities of turbulence scaled by a local maximum velocity are shown, and the mean and fluctuating velocity fields in the cross section are examined in detail.

Main Symbols

b_j	: Nozzle size ($= d$)
c_f	: Local skin friction coefficient in the x -direction
d	: Nozzle diameter
q_τ	: Friction velocity in the x -direction
Re_j	: Reference Reynolds number ($= U_j b_j / \nu$)
U, W	: Mean velocity components in the x - and z -directions, respectively
u, v, w	: Fluctuating velocity components in the x -, y - and z -directions, respectively
u', v', w'	: rms values of fluctuating velocities u, v and w , respectively
U_j	: Jet efflux velocity
U_m	: Maximum velocity on the cross section
U_{my}, W_{my}	: Local maximum velocities in the x - and z -directions, respectively
x	: Coordinate in the jet-axis direction
y, z	: Coordinates normal to the wall and of the spanwise direction, respectively
$y_{0.5}$	: Half-value height of the velocity within the symmetry plane
y_m	: Maximum velocity height within the symmetry plane
$z_{0.5}$	: Half of the half-value width in the z -direction at the position of $y = y_m$
β	: Angle of the wall-flow direction to the jet-axis

2. Experimental Apparatus and Method

The wind tunnel used in this experiment was equipped with an inverter type vortex blower (output: 0.4 kW) as an air supply source and a settling chamber of approx. 78 mm in diameter with a honeycomb (cell size: 8 mm, height: 60 mm) and four sheets of screens (mesh #32, wire diameter: 0.3 mm). The jet was discharged from a circular nozzle of the exit diameter $d = 20$ mm, connected with the settling chamber. The measuring flat plate was positioned to be in parallel with the jet axis and aligned with the lower end of the nozzle. The axial length and width of the measuring plate were 2.4 m and 1.8 m, respectively.

Around the nozzle exit, a plate of the height of 800 mm was attached normally to the measuring plate.

Figure 1 shows the brief overview of the flow field and coordinate system. The experiment was conducted with the reference Reynolds number $Re_j = 1 \times 10^5$ formed from the jet efflux velocity U_j and the nozzle size b_j (= nozzle exit diameter d), when U_j was approx. 80 m/s. Figure 2 shows the velocity distribution at the nozzle exit. This figure shows that the mean and fluctuating velocity profiles were uniform. Let the origin of the coordinate system be on the wall at the nozzle exit, the x -axis be in the flow direction, the y -axis normal to the wall, and the z -axis normal to the x - and y -axes. The maximum velocity in a given cross section was defined as U_m , and the height from the wall to this maximum-velocity position was defined as y_m . The half-value height of the velocity in the symmetry plane was defined as $y_{0.5}$, and the width between the points at which the mean velocity became 1/2 of the maximum velocity at constant height $y = y_m$ in the z -direction was defined as $2 z_{0.5}$. In what follows the quantities defined above will be used for the reference of length and velocity scales.

For the measurement of velocities, a constant-temperature hot-wire anemometer and hot-wire probes (made of tungsten wires of diameter of 5 μm and operating length of 1 mm) were used. For point measurements, I-, X- and V-type hot-wire probes were mainly used, and rotated I-type probe was used for the measurement of the flow direction in the vicinity of the wall. There is a problem of wall-cooling effect in the vicinity of the wall on the hot-wire measurements. To avoid this problem, an acrylic resin plate with low heat conductivity was used for the wall material, and then we did not consider that any correction was necessary for the wall-cooling effect in the present experimental condition ($y > 0.2$ mm). The hot-wire output signals were sampled at the conversion rate of 10 kHz on an A/D converter, and then stored and processed on a PC. The processing of the output signal from the cross-wire probe and the rotated hot-wire probe was based on Ref. [14].

3. Experimental Results and Discussion

3.1 Development of the Flow

From the experimental results for confirming the flow development by using the I-type probe, the distributions in the y - and z -directions of the mean velocity U and the rms value of the fluctuating velocity u' made dimensionless by the maximum velocity U_m and the half-value height $y_{0.5}$ or the half of the half-value width $z_{0.5}$ are shown in Figs. 3 and 4, respectively. Here, the distributions in the y -direction are those on the symmetric plane ($z = 0$) and in the z -direction at the maximum velocity height ($y = y_m$) over the range of $x/b_j = 30$ -80; for the z -direction, only one-side field of $z \geq 0$ are shown because of the symmetric

Fig. 1 Flow field, nomenclature and coordinate system.

Fig. 2 Velocity distributions of the discharged jet flow.

Fig. 3 Dimensionless distributions of the streamwise mean velocity component.

Fig. 4 Dimensionless distributions of turbulent intensity in the streamwise direction.

property of the flow with respect to $z = 0$. In Figs. 3 and 4 are also shown, for comparison, the results of the experiments by Fujisawa *et al.*⁽⁷⁾ and Abrahamsson *et al.*⁽¹¹⁾, and the results of the plane-wall jet (hereinafter abbreviated as “PWJ”) measured by the present authors⁽²⁾. The nozzle used by Abrahamsson *et al.*⁽¹¹⁾ and their experimental conditions were almost the same as in this experiment. Their measurements were mainly made at the position of $x/b_j = 80$ for the Reynolds number of $Re_j = 0.79 \times 10^5$. On the other hand, Fujisawa *et al.*⁽⁷⁾ used the developed flow in a pipe with quadrate cross section as an efflux jet, which makes the initial condition of the jet different from this study. They obtained the experimental results mainly for $x/b_j = 50$ -150 at $Re_j = 0.6 \times 10^5$. Although the nozzle exit condition may affect the developing process of the wall jet, the fully developed flow in the field far from the nozzle becomes independent of the upstream history according to Sforza *et al.*⁽¹⁵⁾ described later. This study, dealing with this flow field, will compare the experimental results without referring particularly to the difference in the jet efflux conditions hereinafter as well. Incidentally, referred to PWJ is the result of $x/b_j = 126$ at $Re_j = 0.15 \times 10^5$.

Firstly, from Fig. 3(b) showing the mean velocity distribution in the y -direction, it is understood that the dimensionless distribution of the three-dimensional wall jet (hereinafter abbreviated as “3DWJ”) maintains the similar profile within the axial range indicated in this figure. It is also confirmed that this distribution is also in agreement with the distributions of 3DWJ measured by other researchers and that of PWJ. So is the case with the mean velocity distribution in the z -direction shown in Fig. 3(a) with the dimensionless distribution being similar. As to the fluctuating velocity distribution shown in Fig. 4, the similarity of the distributions for $x/b_j \geq 50$ is satisfied substantially both in the y - and z -directions. From these results, it may be said that the fully developed flow is achieved for $x/b_j \geq 50$. Note, however, that the position in which the aspect ratio of the wall jet in the cross section, *i.e.*, $z_{0.5}/y_{0.5}$, becomes constant is, as described later, far below downstream. If this is taken as a condition of the developed flow⁽¹⁶⁾, the flow in this experiment could not be said as fully-developed. In comparison between the 3DWJ and the PWJ, there is a large difference in the fluctuating velocity distribution in the y -direction (Fig. 4(b)). The fluctuating velocity of the 3DWJ is larger than that of the PWJ in the vicinity of the wall up to approx. 1.6 times. The y -position indicating its maximum value is near the wall side. Such distribution

Table 1 Specification.

	dy_m/dx	$dy_{0.5}/dx$	$dz_{0.5}/dx$	$U_m \sim x^n$
3DWJ (present)	0.0085	0.0548	0.245	-1.29
PWJ (Yamashita <i>et al.</i> 1999)	0.0117	0.0750	-----	-0.511

difference is treated in Section 3.3.

Figures 5(a) and (b) show the downstream developments of the maximum velocity height y_m , and the half-value height $y_{0.5}$ and half of the half-value width $z_{0.5}$, respectively. Figure 6 shows the decay character of the maximum velocity U_m in the flow direction. Every length scales of the wall jet shown in Figs. 5(a) and (b) increase lineally in the flow direction; their spread rates are summarized in Table 1. The spread rate of the lateral half-value width, $dz_{0.5}/dx$, is about 4.5 times larger than that of the half-value height. This anisotropic development rate is one of the characteristics of the 3DWJ. The variation in the ratio of the jet-widths in both directions, $z_{0.5}/y_{0.5}$, which indicates the aspect ratio of the flow fields in the cross section, in the flow direction is shown in Fig. 5(c). This ratio increases sharply within the range of $20 < x/b_j < 50$, exceeding 3. It continues gradual increase and takes the value $z_{0.5}/y_{0.5} \approx 3.6$ at $x/b_j = 100$. Incidentally, the broken line in the figure indicates the value of $z_{0.5}/y_{0.5}$ obtained from the assumption of the linear increase in each half-value width; the asymptotic value in the far downstream is about 4.5.

The values of the spread rate, obtained so far by several researchers, depends on the jet discharging conditions, and are distributed over a certain range⁽³⁾⁽¹¹⁾. The values obtained in this experiment fall in this range. When comparison is made in the increase rates dy_m/dx and $dy_{0.5}/dx$ with the PWJ, it is found that the rates in the PWJ are larger by about 1.4 times. This difference has also been pointed out by other researchers⁽¹⁷⁾, who indicated the intensity of the entrainment in the outer region.

Development of 3DWJ can be, according to Sforza *et al.*⁽¹⁵⁾ who investigated the jets from nozzles of various shapes and aspect ratios, classified into 3 stages: (1) jet core (PC) region where the maximum velocity coincides with the jet exit velocity, (2) characteristic decay (CD) region where the decay of the velocity depends on the jet discharging conditions, and (3) radially decaying (RD) region where the jet spreads radially irrespective of the upstream conditions. The characteristics of these three regions are clearly exhibited in

Fig. 5 Variation of length scales.

Fig. 6 Decay of maximum velocity.

the decay character of the maximum velocity shown in Fig. 6, where the decaying rate is different between the CD region and the RD region. In this experiment, the boundary between the CD and RD regions is $x/b_j \approx 20$, and the maximum velocity U_m decays as the power of x in the RD region; its exponent is -1.29. As Padmanabham *et al.*⁽⁹⁾ and Abrahamsson *et al.*⁽¹¹⁾ have shown, there are differences among researchers as to the value of the exponent whose distribution is extending over the range from about -1.1 to -1.3.

In order to make the value of the exponent clear, the virtual origin of the jet should be firstly determined. In 3DWJ, however, there are two virtual origins, that is, ones for the half-value height $y_{0.5}$ and the half-value width $z_{0.5}$: say, x_{0y} and x_{0z} , respectively. We found in this flow field that $x_{0y}/b_j = -8$ and $x_{0z}/b_j = 13$. Newman *et al.*⁽¹⁷⁾ conducted similarity analysis neglecting the wall shear stress and the pressure gradient, and obtained that the maximum velocity was proportional to the -1st power of the distance in the flow direction, assuming the linear development of the jet width scales. They proposed the virtual distance $x' = \{(x - x_{0y})(x - x_{0z})\}^{1/2}$ for the flow directional coordinate in their analysis. After Newman *et al.*, the variation in the maximum velocity U_m in this flow with respect to the virtual distance x' is also shown in Fig. 6. In this case, the exponent becomes -1.16, and comes closer to -1 than -1.29 obtained with the distance x . This supports the results of similarity analysis by Newman *et al.*⁽¹⁷⁾ and shows the importance of how to take the flow directional coordinate. However, in order to make the experimental determination for the universal value of the exponent, the measurement of the surface shear stress is indispensable.

3.2 Mean Velocity Field in the Cross Section

In this and subsequent sections we investigate the 3DWJ flow within the cross section. The noting position is mainly $x/b_j = 60$ which is within the flow developed region confirmed in Section 3.1. The mean velocity components to be treated here are the axial and lateral component, U and W . The component in the direction normal to the wall, V , is not treated here, because, according to the estimation based on the continuity equation, it is not large enough to assure good precision in the measurement with the X-type hot wire.

Figure 7 shows the contour map of the mean velocity U and the distribution of the mean velocity W . From the contour of the mean velocity U of Fig. 7(a), it is seen that the distribution, which should have been a concentric circle when there is no wall, is spread in the z -direction under the influence of the wall existence. Compared with the spread rate of the half-value width of the circular free jet (about 0.09⁽¹⁸⁾), the development of the 3DWJ in the y -direction seems to be suppressed. This lateral elongation can be clearly seen on the distribution of the mean velocity W in Fig. 7(b), which shows the existence of significant lateral flow. Each profile of W takes the maximum value in the vicinity of the wall. This maximum value is largest near $z = z_{0.5}$ ($z/b_j = 11.3$) with respect to the lateral position. Figure 8 shows the distributions of the mean velocities U and W made dimensionless by the nozzle diameter b_j and the local maximum velocities U_{my} and W_{my} at each z -position. From these figures, it is understood that each distribution of both velocity components falls substantially on one curve. Figure 9 shows the vector locus of the mean velocity in the

Fig. 7 (a) Contour map of mean velocity U and (b) profiles of mean velocity components W in the cross section.

Fig. 8 Dimensionless distributions of the mean velocity component, (a) U and (b) W .

Fig. 10 Distributions of the local maximum velocity, U_{my} and W_{my} , in the spanwise direction.

plane parallel to the wall, made dimensionless by U_{my} and W_{my} just the same. Although the data in the vicinity of the wall is somewhat deficient, it is presumable that the vector locus on the wall side from the maximum velocity height, *i.e.*, in the inner layer, almost coincides with the straight line running from the origin toward the maximum velocity (1, 1). This suggests that the mean flow direction in the inner layer does not almost change in the inner layer, that is a characteristic of pressure-driven three-dimensional boundary-layer⁽¹⁹⁾. Hence, it is expected for the 3DWJ that the law of the wall will be valid near the wall like that of the three-dimensional boundary layer, but in this study we have not acquired the data sufficient enough to examine this point. On the other hand, the mean flow in the outer layer changes rapidly its direction, and at the position of $U \approx 0.5 U_{my}$ ($y \approx y_{0.5}$) the mean flow direction coincides nearly with the x -direction. Over this position, the mean flow direction turns slightly toward the jet axis.

The variations in the maximum velocities U_{my} and W_{my} in the z -direction are shown in Fig. 10. U_{my} has its maximum value at $z = 0$ and decreases monotonically toward the outer edge of the jet. W_{my} is an odd-function with respect to z with $W_{my} = 0$ at $z = 0$, and after reaching about $0.18 U_m$ at $z \approx 0.8 z_{0.5}$, it decreases toward the outside. The variation in the length scales in the z -direction is given in Fig. 11, where $(y_m)_z$ and $(y_{0.5})_z$ indicate the

Fig. 9 Polar plots of the mean velocity vector at $x/b_j = 60$. (RHW: rotating hot-wire method)

Fig. 11 Variations of the jet height in the spanwise direction.

Fig. 12 Angles of the mean velocity vector in the inner layer to the x -axis.

maximum velocity height and half-value height in a given z -position, and they vary little in the z -direction. The variation in the mean flow direction in the inner layer, as represented by $\beta = \tan^{-1}(W_{my} / U_{my})$, in the z -direction is shown in Fig. 12. It can be seen from this figure that this angle, β , increases lineally up to $\beta = 15^\circ$ at $z \approx 0.8 z_{0.5}$, and beyond that, its increase rate becomes gradual.

The above discussion confirms the substantial validity of the mean flow model of Newman *et al.*⁽¹⁷⁾ in the region of $y < y_m$ and $|z| < z_{0.5}$. However, the model of Newman *et al.*⁽¹⁷⁾ is not satisfactory, in particular, to describe the three-dimensional behavior of the flow in the outer layer of $y > y_m$. As to the almost fully turbulent-flow region of $y_m < y < y_{0.5}$, the flow model in the (turbulent/non-turbulent) intermittent region of $y > y_{0.5}$ and the aforementioned law of the wall in the inner layer, further exhaustive experiments would be needed, which the authors intend to do.

3.3 Fluctuating Velocity Field in the Cross Section

Fluctuating velocity components measured by using V-type and X-type probes are dealt here. Figure 13 shows the r.m.s. values of the fluctuating velocity components (u , v , w) made dimensionless by the resultant value of the local maximum velocity, $Q_{my} = (U_{my}^2 + W_{my}^2)^{0.5}$. The double turbulent kinetic energy, $\overline{q^2} = \overline{u^2} + \overline{v^2} + \overline{w^2}$, and the correlation between the fluctuating velocity components, *i.e.*, the Reynolds shear stresses $-\rho \overline{uv}$ and $-\rho \overline{uw}$, made dimensionless by Q_{my}^2 , are shown in Figs. 14 and 15, respectively. In these figures the results of the plane-wall jet measured by the authors⁽²⁾ are also shown for comparison with broken lines.

It is clear from these results that each profile for $y/y_{0.5} \leq 1$ varies with z -position and that in the outer layer it shows a substantially similar one. The distribution of $\overline{uw}$ for $y/y_{0.5} > 1.2$, in particular, is asymptotic to zero, which is consistent with that the mean velocity W in this region is almost zero, *i.e.*, the mean flow direction is roughly aligned with the x -axis. Hence, it is presumable that the flow in the uppermost region from the height of $y \approx y_{0.5}$ has the turbulent structure similar to the plane wall jet and that it spreads to some extent in the lateral direction.

On the other hand, for $y/y_{0.5} \leq 1$ the scaling applied here seems not to be appropriate. All the scaled values of $\overline{q^2}$, $\overline{uv}$ and $\overline{uw}$ shown in Figs. 14 and 15 increase as the z -position goes outside; in particular, the rate of increase in the $\overline{uw}$ distribution is considerably large. Moreover, as described in Section 3.1, the turbulent quantities of the 3DWJ is considerably large in the vicinity of the wall compared with those of the PWJ, and the y -positions where their maximum values are reached are nearer the wall. As to these findings intimate considerations

Fig. 13 Dimensionless distributions of the turbulent intensity, (a) u' , (b) v' and (c) w' .

Fig. 14 Dimensionless distributions of the double turbulent kinetic energy.

based on the turbulent energy and the Reynolds stress transport equations should be made. For example, taking the production terms in the transport equation for $\overline{uw}$, which are $\overline{vw} \partial U / \partial y$, $\overline{uw} \partial W / \partial y$ and $\overline{w^2} \partial U / \partial z$, into consideration, an appropriate scaling method should be identified. Supposing a free jet with no wall, the greatest of the contribution to the productions of $\overline{uw}$ and of the turbulent kinetic energy is $\overline{w^2} \partial U / \partial z$ and $\overline{uw} \partial U / \partial z$, respectively. If each distribution of $\overline{u^2}$, $\overline{w^2}$ and $\overline{uw}$ is compared at the height of $y = y_m$ with the results of the circular free jet⁽¹⁸⁾, there is much correspondence with each other. However, there is a great difference in the spread rate of the jet between the two: $dz_{0.5} / dx = 0.09$ in the circular free jet, while $dz_{0.5} / dx = 0.24$ in this flow, the latter being about 2.7 times as much as the former. This difference may be attributed to the existence of the wall and the generation of secondary flows.

Lastly, the Reynolds shear stress acting in the plane normal to the x -axis is investigated. Figure 16 shows the resultant of the Reynolds shear stresses $-\rho \overline{uv}$ and $-\rho \overline{uw}$ in a vector diagram. The broken lines in this figure are the constant velocity lines reinserted from Fig. 7(a). An consideration of the secondary flow based on this kind of diagram has been made earlier by Nakamura *et al.*⁽²⁰⁾ on the three-dimensional square jet, and the validation of the scalar eddy viscosity has been examined. In 3DWJ also, the Reynolds shear-stress vectors are almost orthogonal to the constant velocity lines in the same way as the results of Nakamura *et al.*⁽²⁰⁾. Here, it should be mentioned that this examination does not directly attest the generation of the secondary flow. As indicated by Launder & Rodi⁽⁴⁾, the transport equation of the mean vorticity in the flow direction should be inquired to clarify the generation process of the secondary flow. For this purpose, the measurement of the distribution of $\overline{vw}$ in the cross section is absolutely necessary, but, due to difficulties in this measurement, this kind of inquiry has hardly been done until now.

4. Conclusion

The results of this study on the three-dimensional wall jet (3DWJ) are summarized as follows:

(1) The aspect ratio of the flow in the cross section increases in the flow direction. Its asymptotic value in the far downstream is about 4.5. The RD region of this flow ranges in the downstream from $x / b_j \approx 20$. The decay of the maximum velocity in this region is proportional to the -1.16 power of the virtual distance.

(2) On the cross section of the developed region, the distributions of the mean velocities U and W in the y -direction are almost similar irrespective in z -position when they are made

Fig. 15 Dimensionless distributions of the Reynolds shear-stress, (a) $\overline{uv}$ and (b) $\overline{uw}$.

Fig. 16 Map of the Reynolds shear-stress vectors and contour lines of the streamwise mean velocity.

dimensionless by the local maximum velocities U_{my} and W_{my} , respectively. The mean flow direction is constant in the inner layer of $y/y_m \leq 1$. Outside of this layer the flow skews greatly, and for $y/y_{0.5} > 1$ its direction becomes almost aligned with the jet axis. The mean flow angle in the inner layer linearly increases within the range of $|z/z_{0.5}| < 0.8$.

(3) Any distribution of the turbulent statistics falls almost on one curve when made dimensionless by the local maximum velocity Q_{my}^2 for $y/y_{0.5} > 1.2$, and is also in good agreement with the distribution of the PWJ. The distribution of these quantities for $y/y_{0.5} \leq 1$ with the same scaling is highly dependent on the z -position, and, the more the distance from the jet axis is, the larger any distribution is. The Reynolds shear-stress vectors acting on the plane normal to the x -axis are almost orthogonal to the isopleths of the mean velocity component in the axial direction; the validity of the hypothesis of the scalar eddy viscosity is verified.

References

- (1) Hanjalic, K. and Obi S. (eds.), *Proceedings of the 6th ERCOFTAC/IAHR/COST Workshop on Refined Flow Modeling*, Delft Univ. Tech., The Netherlands (1997-6).
- (2) Yamashita, S. and Inoue, Y., *Proceedings of the 10th Symposium on Turbulent Shear Flows*, Penn State, USA, (1995-8), pp.14.1-14.6.
- (3) Launder, B.E. and Rodi, W., *Progress in Aerospace Sciences*, Vol.19 (1981), pp.81-128.
- (4) Launder, B.E. and Rodi, W., *Annual Review of Fluid Mechanics*, Vol.15 (1983), pp.429-459.
- (5) Koso, T. and Ohashi, H., *Transactions of the Japan Society of Mechanical Engineers*, Series B, Vol.47, No. 418 (1981), pp.1002-1110.
- (6) Koso, T. et al., *Journal of the Visualization Society of Japan*, Vol.10, Suppl.-2 (1990), pp.53-58.
- (7) Fujisawa, N. and Shirai, H., *Transactions of Japan Society of Aeronautical and Space Sciences*, Vol.32 (1989), pp.35-46.
- (8) Matsuda, H. et al., *Transaction of the ASME, Journal of Fluids Engineering*, Vol.112 (1990), pp.462-467.
- (9) Padmanabham, G. and Lakshmana Gowda, B.H., *Transaction of the ASME, Journal of Fluids Engineering*, Vol.113 (1991), pp.620-634.
- (10) Sullivan, P. and Pollard, A., *Measurement and Science Technology*, Vol.7 (1996), pp.1498-1516.
- (11) Abrahamsson, H. et al., *Internal Rep 97/1*, Chalmers Univ. Tech., Sweden, (1997).
- (12) Craft, T.J. and Launder, B.E., *Journal of Fluid Mechanics*, Vol.435 (2001), pp.305-326.
- (13) Obi S., *Proceedings of the 11th Computational Mechanics Conference of the Japan Society of Mechanical Engineers*, (1998-11), No.134.
- (14) Yamashita, S., *Kikai no Kenkyu*, Vol.45 (1993), pp.1280-1286.
- (15) Sforza, P.M. and Herbst, G., *AIAA Journal*, Vol.8 (1970), pp.276-283.
- (16) Khritov, K.M. et al., *AIAA paper*, (2002), No.2002-0732.
- (17) Newman, B.G. et al., *Aeronautical Quarterly*, Vol.23 (1972), pp.188-200.
- (18) Ninomiya, N. and Kasagi, N., *Transactions of the Japan Society of Mechanical Engineers*, Series B, Vol.59, No.561 (1993), pp.1532-1538.
- (19) Johnston, J.P., *Transaction of the ASME, Journal of Basic Engineering*, Vol.80 (1960), pp.233-248.
- (20) Nakamura, I. et al., *Transactions of the Japan Society of Mechanical Engineers*, Vol.44, No.388 (1978), pp.4197-4205.