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TURBULENT DIFFUSION OF A THREE-DIMENSIONAL WALL JET*

(2ND REPORT, TURBULENT STRUCTURE)

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In order to examine the diffusion of a slightly heated jet on a plane wall, intermittency factors, crossing frequencies, conditional zone averages, power spectrum densities and probability densities of velocity and temperature as a passive scalar were evaluated by digital processing of instantaneous temperature and three velocity components. The intermittency factor distributions indicate that intermittent regions extend more in spanwise direction than in normal direction. This presumably results in a larger entrainment from spanwise edges and explains the cause of anisotropic growth of the three-dimensional wall jet observed in the 1st report. Turbulent zone averages of velocity and temperature are larger than those in non-turbulent zones. Probability densities of velocity and temperature have only one peak and their spectra have no spike in far field from the jet exit. Flow field is characterized by rather random and three dimensional turbulence. These results are confirmed by flow visualization of cross sections normal to jet axis.

1. INTRODUCTION

The purpose of this study is to describe the turbulent diffusion of a three-dimensional incompressible wall jet using measured characteristics such as intermittency factors, crossing frequencies, conditional zone averages, spectra and probability densities of velocity and temperature as a passive scalar. The jet is heated slightly and issued from a semi-circular tube into a quiescent air along a plane wall.

In previous report⁽¹⁾, the distributions of mean and turbulent characteristics such as mean velocity, mean temperature, Reynolds stress and turbulent heat flux were examined, and an interesting feature that the mean velocity and temperature field extends more in spanwise direction than in normal direction was found. It was also revealed that the turbulent transport of momentum and heat in spanwise direction is essentially stronger than in normal direction, which agrees with the observed anisotropic growth of the mean velocity and temperature, but the reason for this anisotropic growth remains unexplained.

A three-dimensional turbulent wall jet has a free turbulent shear layer which is characterized by the presence of a sharp, randomly moving interface⁽²⁾ separating the turbulent from the non-turbulent

region. The most important characteristics of this interface is intermittency, and this is thought to play an important role in the entrainment of surrounding air. Therefore it is significant to investigate the intermittency for understanding the mechanism of the observed anisotropic growth of three-dimensional wall jets. It is equally significant to evaluate power spectrum densities and probability densities of velocity and temperature, in order to study the turbulent transport by large-scale organized motion⁽³⁾ which is observed in many cases of turbulent shear flow.

Less attention has been given to the turbulent structure of three-dimensional wall jets. Catalano et al.⁽⁴⁾⁻⁽⁶⁾ studied the turbulent structure of a circular jet on a curved wall and they examined the intermittency factors, auto-correlations, cross-correlations and power spectrum densities. However, probability densities and conditional zone averages of velocity and temperature which are essential indications of the mechanism of turbulent mixing in three-dimensional wall jets, seem to be unavailable so far.

In this study, intermittency indicator functions which indicate the presence of turbulence were reduced from instantaneous three velocity components, and the intermittency factors, crossing frequencies and conditional zone averages were evaluated. Power spectrum densities and probability densities were also evaluated. All the properties presented in this paper were evaluated by digital processing of instantaneous temperature and three velocity components. In addition to these measurements, flow visualization pictures of cross sections normal to jet axis were examined to understand the turbulent structure of a three-dimensional wall jet.

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NOMENCLATURE

- $b_{\gamma y}$: spanwise amplitude of turbulent/non-turbulent interface (m) Eq. (6), Fig.3
 $b_{\gamma z}$: normal amplitude of turbulent/non-turbulent interface (m)
 d_e : equi-area-diameter of jet exit (m)
 f : frequency (Hz)
 f_{γ} : crossing frequency (of turbulent/non-turbulent interface) (Hz)
 I : intermittency indicator function Eq. (1)
 k : turbulent kinetic energy $= (u'^2 + v'^2 + w'^2)/2$ (m^2/s^2)
 p : probability density, Eq.(11)
 P_u, P_v, P_w, P_T : power spectrum densities of u, v, w and T
 S_1, S_2 : criterion functions, Eq.(2) and (3)
 T : temperature (excess of surroundings) ($^{\circ}\text{C}$)
 t : time (s)
 t_n : sampled period (s)
 u, v, w : velocity components of x, y, z directions (m/s)
 x, y, z : Cartesian coordinates in Fig.1 (m)
 γ : intermittency factor, Eq.(4) (dimensionless)
 Δt : sampling interval (s)
 μ_k : k -th moment of velocity fluctuation Eq.(15) (dimensionless)
 σ : standard deviation, Eq.(14)
 Subscripts (See Fig.1)
 j : values at jet exit ($\bar{x}=0$)
 m : maximum values in normal profile
 M : maximum values in spanwise profile
 $u_{1/2}$: velocity half width
 $T_{1/2}$: temperature half width
 Superscripts
 $(-)$: time-mean values (conventional averages) or non-dimensional coordinates $\bar{x} = x/d_e, \bar{y} = y/d_e, \bar{z} = z/d_e$
 $(\prime)$: fluctuation components
 $(\sim)$: turbulent zone averages (conditional averages), Eq.(8)
 $(\approx)$: non-turbulent zone averages (conditional averages), Eq. (9)

2. EXPERIMENTAL APPARATUS, TECHNIQUES AND CONDITIONS

Experimental apparatus and conditions are identical to those of previous report.

2.1 EXPERIMENTAL APPARATUS AND TECHNIQUES

A slightly heated air jet is blown from a semi-circular tube into a quiescent air along a smooth plane wall (See Fig.1). The velocities at the exit have the profile of a fully developed turbulent pipe flow and the temperature profile at the exit is relatively uniform.

Data of instantaneous temperature and three velocity components used in this paper are the same as those in the previous report. Therefore, only the essence of experimental techniques is to be described here. The instantaneous temperature and three velocity components were obtained simultaneously by the digital signal processing of the outputs from four hot wires

having different wire temperatures and different angle settings⁷⁾. The outputs of the hot wire anemometers were recorded on an FM data recorder, and thereafter digitized and computed to evaluate instantaneous temperature and three velocity components. The signals for 5 seconds were sampled and digitized with an inter-

Fig.1 Coordinate system and schematic representation of velocity and temperature field

Fig.2 Typical time traces (at $\bar{x}=10$, $\bar{y}=1.29$, $\bar{z}=0.29$; $\bar{u}/\bar{u}_j=0.215$, $\bar{T}/\bar{T}_j=0.338$, $\gamma=0.853$)

val of 100 μ s on each channel, each sample being 12 bits of information. This sampling covers the frequency range of 0.1Hz to 5kHz in the signals.

2.2 EXPERIMENTAL CONDITIONS The jet blows out from a semi-circle which is half a circle of nearly 50mm diameter. The area of the jet exit is equal to the area of a circle of 34.9mm diameter ($=d_e$). The maximum velocity and temperature relative to the surroundings at the exit are fixed at $\bar{u}_j=31.8 \begin{smallmatrix} +0.05 \\ -0.17 \end{smallmatrix}$ m/s and $\bar{T}_j=10.50 \begin{smallmatrix} +0.02 \\ -0.30 \end{smallmatrix}$ °C. Then, the corresponding jet Reynolds number is $Re_j = \bar{u}_j d_e / \nu = 6.62 \times 10^4 (\pm 0.08 \times 10^4)$. The estimated ratio of buoyancy to inertia at the jet exit is 1.3×10^{-3} , thus making the effect of buoyancy negligible.

3. PRESENTATION AND ANALYSIS OF RESULTS

3.1 INTERMITTENCY AND CONDITIONAL ZONE AVERAGES

Intermittency indicator function I is defined as Eq.(1) in the turbulent shear layer between the jet and surrounding air (See Fig.3).

$$I(x, y, z, t) = \begin{cases} 1 & \text{for turbulent} \\ 0 & \text{for non-turbulent} \end{cases} \quad \dots\dots\dots (1)$$

The procedure for determining $I(t)$ has been discussed in many studies. The procedure employed in this paper is based essentially on that of Hedley and Keffer⁽⁹⁾ which was applied successfully to a two-dimensional boundary layer⁽⁹⁾. The velocity fluctuations in turbulent zones have relatively higher intensity and frequency than in non-turbulent zones. Therefore, the velocity derivatives such as $|\partial u / \partial t|$ and $|\partial^2 u / \partial t^2|$ in turbulent zones are markedly greater than those in non-turbulent zones.

In this study, the criterion functions S_1 and S_2 were used, which are the extension of Hedley and Keffer's criteria to three-dimensional cases and are given by;

$$S_1(j\Delta t) = S_{1j} = \frac{\Delta t^2}{1 + t_s/\Delta t} \sum_{i=j-t_s/2\Delta t}^{i=j+t_s/2\Delta t} \left\{ \left(\frac{\Delta u}{\Delta t} \right)^2 + \left(\frac{\Delta v}{\Delta t} \right)^2 + \left(\frac{\Delta w}{\Delta t} \right)^2 \right\}_i \quad \dots\dots\dots (2)$$

$$S_2(j\Delta t) = S_{2j} = \frac{\Delta t^4}{1 + t_s/\Delta t} \sum_{i=j-t_s/2\Delta t}^{i=j+t_s/2\Delta t} \left\{ \left(\frac{\Delta^2 u}{\Delta t^2} \right)^2 + \left(\frac{\Delta^2 v}{\Delta t^2} \right)^2 + \left(\frac{\Delta^2 w}{\Delta t^2} \right)^2 \right\}_i \quad \dots\dots\dots (3)$$

Then, $I(t) = 1$ (turbulent) was assigned when both S_1 and S_2 exceeded the threshold levels. The smoothing period t_s was determined as $t_s/\Delta t = 4$ ($\Delta t = 100 \mu$ s). The threshold levels were selected by comparing $I(t)$ and three velocity components in the time traces and by referring to the intermittency distributions of free jets⁽¹⁰⁾⁻⁽¹³⁾. The threshold levels were assumed to be constant for a fixed $\bar{x}$. This signal processing was done digitally by a computer. Fig.2 shows the typical time traces of three velocity components, criterion function S_1 , intermittency indicator function I , turbulent kinetic energy k , Reynolds stress $u'v'$, temperature and turbulent heat flux $T'v'$.

Fig.3 Schematic representation of intermittency and amplitude of turbulent/non-turbulent interface

3.1.1 Intermittency factor and crossing frequency

Intermittency factor γ is defined as an average of the intermittency indicator function I .

$$\gamma = \bar{I} = \frac{1}{t_n} \int_0^{t_n} I(t) dt \quad \dots\dots\dots (4)$$

Crossing frequency f_γ is defined as passing frequency of turbulent/non-turbulent interface and given by pulses-per-second of the intermittency indicator function I . Fig.4 shows the typical normal distributions of γ and f_γ with mean velocity $\bar{u}$ and temperature $\bar{T}$. The distribution of intermittency factors γ resembles a Gaussian cumulative profile and the distribution of crossing frequencies f_γ has its maximum at a position where $\gamma \approx 0.5$. The intermittent region where $0 < \gamma < 1$ and $f_\gamma > 0$ is located rather on the outer border of the mean velocity and temperature profiles.

The distributions of intermittency factors at $\bar{x} = 2, 5, 10$ and 20 which are normalized by the velocity half widths, are presented in Fig.5. Both normal and spanwise profiles resemble Gaussian cumulative profiles and become wider with increasing $\bar{x}$. The spanwise profiles of γ extend considerably wider than the normal

Fig.4 Typical mean velocity, mean temperature, intermittency factor and crossing frequency

ones. A fully developed γ profile of plane free jets^(2,4) is included in Fig.5(b). The spanwise profile of γ at $\bar{x} = 20$ is essentially wider and is located more outward than that of plane free jets, whereas the profile at $\bar{x} = 20$ appears to be still developing. The intermittency factors are plotted in Fig.6 on Gaussian probability scale to examine the consistency with the Gaussian cumulative profiles which are in good agreement with the distributions of intermittency factors of plane boundary layer, wake and jet⁽²⁾⁽¹⁴⁾. The Gaussian cumulative profiles expressed by Eq.(5) become straight lines on the probability scale.

$$\gamma(\eta) = 0.5 \left\{ 1 - \operatorname{erf} \left(\frac{\eta - b}{a} \right) \right\} \quad \dots\dots\dots (5)$$

($\eta = y$ or z , a and b : constant coefficients)

The normal profiles of γ shown in Fig.6(a) indicate good agreement with the Gaussian cumulative profiles, whereas the low γ regions of spanwise profiles shown in Fig.6(b) extend more outward than those of Gaussian cumulative profiles. Both normal and spanwise profiles of crossing frequency f_γ have their maxima at positions where $\gamma \approx 0.5$ for almost all the $\bar{x}$ studied, for example Fig.4. This finding has been observed also in free jets⁽²⁾⁽¹⁴⁾ and boundary layer⁽¹⁵⁾.

Corrsin and Kistler⁽²⁾ examined the standard deviations of instantaneous location of turbulent/non-turbulent interface which are given as the square root of the second moment of $\partial\gamma/\partial y$ with y -origin chosen so that $\partial\gamma/\partial y$ has zero first moment. However in this study, the amplitudes b_γ of turbulent/non-turbulent interface shown in Fig.7 were calculated simply by Eq.(6).

$$b_{\gamma y} = y|_{\gamma=0.05} - y|_{\gamma=0.95} \quad \dots\dots\dots (6)$$

These amplitudes b_γ can be obtained easily from γ profiles on probability scale with good accuracy. The spanwise amplitudes $b_{\gamma y}$ of turbulent/non-turbulent interface are considerably larger than the normal ones $b_{\gamma z}$ in far field of the jet exit as shown in Fig.7. This presumably results in a larger entrainment from spanwise edges and explains the cause of anisotropic nature of mean velocity, mean temperature and turbulent transport in the three-dimensional wall jet observed in the previous report.

3.1.2 Conditional zone averages of velocity and temperature The velocity and temperature characteristics relative to the moving turbulent/non-turbulent interface were assessed by conditional averaging. The turbulent zone average $\bar{Q}$ of a property Q is given by averaging Q at a point fixed in space throughout the times when the flow is turbulent. The turbulent zone average $\bar{Q}$, non-turbulent average $\bar{Q}$ and conventional average $\bar{Q}$ are defined using the intermittency indicator function I as Eqs.(7), (8) and (9),

(a)

(b)

Fig.5 Intermittency factors
a) normal distributions
b) spanwise distributions

(a)

(b)

Fig.6 Intermittency factors (probability scale)
a) normal distributions
b) spanwise distributions

Fig.7 Amplitudes of turbulent/non-turbulent interface

$$\bar{Q} \equiv \overline{Q(t)} = \frac{1}{t_n} \int_0^{t_n} Q(t) dt \quad \dots\dots\dots(7)$$

$$\bar{\tilde{Q}} \equiv \overline{\tilde{Q}I/I} = \frac{1}{I t_n} \int_0^{t_n} \tilde{Q}(t) I(t) dt \quad \dots\dots\dots(8)$$

$$\begin{aligned} \tilde{\bar{Q}} &\equiv \overline{\tilde{Q}(1-I)/(1-I)} \\ &= \frac{1}{(1-\bar{I}) t_n} \int_0^{t_n} \tilde{Q}(t) \{1-I(t)\} dt \quad \dots\dots\dots(9) \end{aligned}$$

$$\bar{Q} = \gamma \bar{\tilde{Q}} + (1-\gamma) \tilde{\bar{Q}} \quad \dots\dots\dots(10)$$

where Q is a physical property, for example, velocity. Figs.8 and 9 show the conditional zone and conventional averages of velocity and temperature at $\bar{x}=10$ with the intermittency factors. The results are consistent with those obtained in plane and circular free jets^{11,12,13,14} in that the turbulent fluid has higher velocity and temperature than those of the entrained non-turbulent fluid. Therefore, in the intermittent regions the relations $\tilde{u} > \bar{u}$ and $\tilde{T} > \bar{T}$ hold.

Fig.8 Conventional averages and conditional zone averages (normal distributions)
a) velocity b) temperature

Fig.9 Conventional averages and conditional zone averages (spanwise-distributions)
a) velocity b) temperature

3.2 PROBABILITY DENSITY AND POWER SPECTRUM DENSITY

The probability densities and power spectrum densities of velocity and temperature were evaluated to examine the turbulent transport by large-scale organized motion.

3.2.1 Probability densities of velocity and temperature The probability density of velocity $p(u)$ was assessed by Eq.(11).

$$p(u) = \lim_{\Delta u \rightarrow 0} \frac{1}{\Delta u} P_{rob}[u < u(t) < u + \Delta u] \quad \dots\dots(11)$$

When the variable has two levels such as a square wave, its probability density has two peaks. When the variable is completely random, its probability density has a Gaussian distribution. The following relations hold about the probability density $p(u)$, average $\bar{u}$, standard deviation $\sigma = \sqrt{u'^2}$ and k -th moment μ_k .

$$1 = \int_{-\infty}^{\infty} p(u) du \quad \dots\dots\dots(12)$$

$$\bar{u} = \int_{-\infty}^{\infty} u p(u) du = \frac{1}{t_n} \int_0^{t_n} u dt \quad \dots\dots(13)$$

Fig.10 Probability densities of velocity
a) for different normal positions
b) for different spanwise positions

Fig.11 Probability densities of temperature
a) for different normal positions
b) for different spanwise positions

$$\sigma^2 = \int_{-\infty}^{\infty} (u - \bar{u})^2 p(u) du = \frac{1}{t_n} \int_0^{t_n} (u - \bar{u})^2 dt \quad \dots\dots\dots(14)$$

$$\mu_k = \frac{1}{\sigma^k} \int_{-\infty}^{\infty} (u - \bar{u})^k p(u) du$$

$$= \frac{1}{t_n \sigma^k} \int_0^{t_n} (u - \bar{u})^k dt \quad \dots\dots\dots(15)$$

Fig.10 shows the probability densities of velocity at $\bar{x}=10$ and Fig.11 shows the probability densities of temperature. The resolutions of probability density are 0.4m/s of velocity and 0.2°C of temperature. The characters (A,B etc.) in Figs. 10 and 11 indicate the locations where the probability densities are measured, and correspond to the characters in Figs.8 and 9 for the conditional averages.

The probability densities of velocity and temperature have only one peak even in the intermittent regions. This fact suggests that the transport of surrounding air into the inner regions by large-scale motion is not dominant, whereas the transport by large-scale organized motion plays a major role in the initial regions of a plane turbulent shear layer⁽³⁾. The probability densities show a distinct discrepancy with the Gaussian in near wall region and intermittent region. The values of skewness (and 3rd-moment μ_3) of velocity and temperature which are negative in near wall, increase with increasing $\bar{z}$ and become positive in the intermittent region. A similar trend of skewness has been seen in the velocity of pipe flow⁽¹⁷⁾ and in the velocity and the passive heat of plane boundary layer⁽¹⁸⁾.

3.2.2 Power spectrum densities of velocity and temperature

The power spectrum density $P(f)$ was computed by a fast fourier transform (FFT) program⁽¹⁶⁾. Before applying the FFT, the signals were arranged using a data window proposed by Bingham et al. The spectra were smoothed by both ensemble averaging and hanning. The bandwidths Δf_e of the resultant spectra shown in this paper are 8.5Hz for $f \leq 200$ Hz and 30Hz for $f > 200$ Hz. The coefficients of variation are 0.08 for all frequencies. Fig.12 shows the velocity spectra at $\bar{x}=20$ and Fig.13 shows the temperature spectra. The spectra of turbulent kinetic energy are also shown in Fig.14. These spectra are normalized by the mean square σ^2 , and therefore

$$\int_0^{\infty} P(f)/\sigma^2 df = 1 \quad \dots\dots\dots(16)$$

As seen from the figures all the spectra of u , T and k at $\bar{x}=20$ have no spike for all frequencies, whereas the spectra of a circular free jet⁽¹⁹⁾ show spikes at low frequency in regions near the nozzle. This fact suggests that the flow field is characterized by rather random turbulence. The spectra with no spike are common in the fully developed regions of the turbulent mixing layers, for example, a free jet⁽²⁰⁾, a plane shear layer⁽²¹⁾ and a circular jet on a curved wall⁽⁵⁾. The spectra of velocity at high frequencies are expressed well by

the familiar Kolmogoroff's -5/3 power formula over two decades.

Thus the results indicate no evidence to the presence of a periodical large-scale organized motion. The results of the probability density and spectra suggest that the turbulent structure of the three-dimensional wall jet is characterized rather by its random nature and by three-dimensionality effects in far field from exit.

Fig.12 Normalized power spectrum densities of velocity
a) for different normal positions
b) for different spanwise positions

Fig.13 Normalized power spectrum densities of temperature

Fig.14 Normalized power spectrum densities of turbulent kinetic energy

3.3 VISUALIZATION OF CROSS SECTIONS

NORMAL TO JET AXIS A three-dimensional wall jet was visualized by means of dry-ice fog⁽²²⁾. The dry-ice fog was generated by submerging dry-ice cubes into hot water, and it was blown from the jet exit. The jet Reynolds number is 4×10^4 to 8×10^4 and the ratio of buoyancy to inertia at jet exit is $\sim 10^{-3}$, which is practically negligible. To examine the anisotropic growth of this flow, the cross sections normal to the jet axis were illuminated by a thin sheet of light. The width of the light sheet was 2 to 3mm. The pictures were taken from downstream and slightly upper positions.

Fig.15 shows visualization pictures at $\bar{x}=2, 5, 10, 15, 20$ and 30 for three different exposure time, that is, (1) long time exposure (3 to 4 seconds), (2) middle

time exposure ($1/125$ to $1/30$ second) and (3) short time exposure (1 ms). The pictures of long time exposure shown in Fig.15 (1) indicate the time-mean distributions, and demonstrate clearly a strong growth in spanwise direction. The pictures of short time exposure shown in Fig.15(3) indicate relatively instantaneous distributions, and reveal that an irregular interface separating the jet from the surrounding air extends more in spanwise direction than in normal direction. These findings are in accord with the hot wire measurements. The rolling-up motion observed in Fig.15(3c) seems to correspond to that suggested by Catalano et al.⁽⁴⁾, but the occurrence of this motion was uncommon. Thus, the visualization study confirms the rather random turbulent structure observed in the previous section.

Fig.15 Visualization of cross sections normal to jet axis ($\bar{u}_j=10$ to 20m/s)
exposure (1) a, d, e and f : 4s , b and c : 3s
(2) a and b : $1/125\text{s}$, c, d and e : $1/60\text{s}$, f : $1/30\text{s}$ (3) 1ms

Fig.16 Velocity and temperature distributions in a plane normal to jet axis
a) contours of isovelocity
b) contours of isotemperature

Fig.16 shows distributions of velocities and temperatures at $\bar{x}=30$. The contours of isovelocity and isotemperature were drawn using the data at 342 locations measured by a Pitot tube and a thermocouple described in the previous report. The distribution of temperatures shown in Fig.16(b) is physically equivalent to that of dry-ice fog as a passive scalar at $\bar{x}=30$ shown in the picture of Fig.15(1f). The jet edges recognized in the visualization pictures correspond nearly to the contour of $\bar{T}/\bar{T}_m = 0.2$.

4. CONCLUDING REMARKS

The principal results and the turbulent structure inferred from the results are as follows:

The results on intermittency confirm the anisotropic growth observed in previous studies. Namely, in far field from jet exit, the profiles of intermittency factor extend more in spanwise direction than in normal direction, and the spanwise amplitudes of turbulent/non-turbulent interface are essentially larger than the normal ones.

The existence of larger amplitudes in spanwise direction presumably results in a larger entrainment from spanwise edges and explains the cause of the stronger turbulent transport in spanwise direction and of the anisotropic growth of the mean velocity and temperature.

The turbulent zone averages of velocity and temperature are larger than those in non-turbulent regions. The probability densities of velocity and temperature have only one peak and their spectra have no spike in far field from the jet exit.

Thus, the transport of surrounding

air into the inner regions by large-scale motion is supposed to play only a minor role in the turbulent mixing of the three-dimensional wall jet, while the turbulent fluid has higher velocity and temperature than the entrained non-turbulent fluid. The results on the probability density and spectra suggest that, in far field from the jet exit, the turbulent structure of the three-dimensional wall jet is characterized by its random nature and three-dimensionality effects.

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