Turbulent Round Jet Submerged in Dilute Drag Reducing Polymer Solutions

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Abstract

The present paper presents the results of experimental study of the turbulent round jet in dilute polymer solutions. The turbulence characteristics were measured by means of the tracer particle visualization technique. Experimental results show a drastic suppression of small scale turbulence and the increase of integral scale. The anisotropic increase of integral scales in a submerged jet was observed, which implied the strong relationship of the polymer additive with the local turbulent dissipation.

Introduction

The reduction in wall shear stress caused by the polymer additives of high molecular weight has been widely investigated because of its possible great importance in practical applications. Most investigations on drag reduction were done in a round tube or in a flat plate boundary layer flow. Although the number of papers is relatively small, the study of turbulent jets has been another effort toward understanding the flow behavior of the drag reducing polymer solutions.

In an early experiment, Gadd2) visualized the submerged jet of polymer solutions. In his observation, the presence of Polyox WSR–301 caused a significant suppression of the small-scale turbulence. On the other hand, White11) and Goren3) found no visible difference between water and dilute polymer solutions. Recently, Barker1) employed a laser doppler technique to measure the velocity profile and the fluctuation velocity in an axisymmetric submerged jet of polymer solutions. His conclusion agreed with the observation of White11) and Goren3). The gross structure of the submerged jet was not effected by the polymer additive. On the other hand, Shulman et al.9) measured the fluctuating velocity of the submerged jet using a piezoceramic probe. In their experiments, a significant decrease of eddy diffusivity in a dilute polymer solution was observed, and this results corresponded to the observation of Gadd2). The experimental results mentioned above are rather confusing, and more precise experimental work is required.

In this investigation, the authors attempted to explain the effect of the polymer additive on the structure of free turbulence. Turbulent motion of the submerged jet

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was recorded on the high-speed cinefilm which provided the trajectory of tracer particles suspended in polymer solutions. Autocorrelation and space-correlation of the fluctuating velocity were calculated from the analyzed results of cinefilm.

1. Experimental Details

Axisymmetric jet submerged in a plexiglass tank (400 × 400 × 2500 mm) was used in this study. Dilute polymer solutions were run through once only using a large storage tank (1.5 m^3) to minimize the effect of mechanical degradation of polymer additives. The jet was ejected from a convergent nozzle whose area ratio was 10: 1 and the diameter of outlet section was 1 cm. The ambient liquid in the test tank was the same polymer solution as contained in the storage tank.

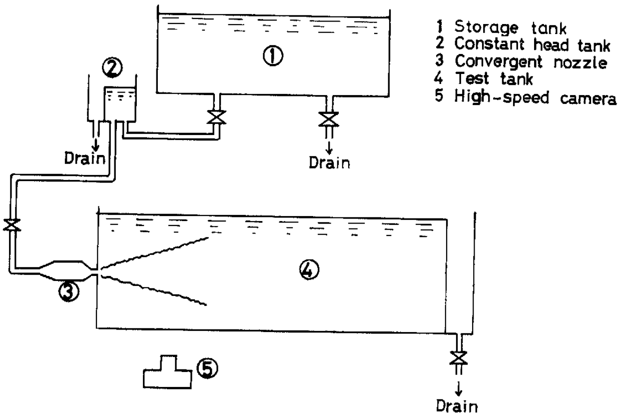


Fig. 1 Flow diagram of the experimental apparatus.

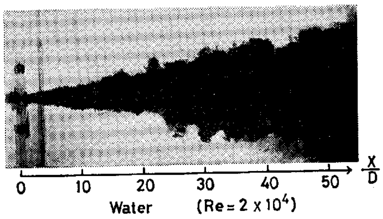
In the preliminary experiments, the jets were coloured by India ink, and behavior of the jets was photographed. The variation of the jet center-line velocity along the jet axis was also measured by a pitot tube in this preliminary experiments.

The pictures of the jets were taken by a high-speed cinecamera (Hitachi-16H) with 100 feet of colour-film. The tracer particles made of polyethylene and coloured with orange fluorescent pigment were suspended into test liquids. The particle diameter, density and concentration were 200 μ, 1.03 g/cm^3 and 0.2 wt% respectively. The tracer particles were illuminated by the parallel light of a mercury lamp which came in the lateral direction of the jet through a slit of 3 mm width. The sampling volume was selected to be 3 mm in the radial direction and 6 mm in the axial direction of the jet. The time intervals between each frame on a film were approximately 2×10^{-3} sec. The flashes of a stroboscope (time interval; 10^{-1} sec) were recorded simultaneously on the film and the correct time interval of each frame was determined from the bright line of the flash light. A film motion analyzer (Bell & Howell model 7399) was used to measure the coordinate differences of a tracer particle between two successive frames. The instantaneous velocity of a particle was determined by axial and radial displacement and time lapse per frame. The velocity of liquid was assumed to be equal to that of tracer particle.

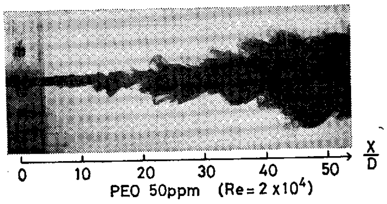
Polyethylene-oxide (PEO: grade ALCOX, E160, supplied by Meisei Chemical Corp.), was used as the polymer additive. The intrinsic viscosity of ALCOX, E160 in water was 1200 cm^3/g. A stabilizer (SANDEX–C), supplied by Meisei Chemical Corp., was added to prevent the degradation of polymer additive. Tap water was used to dissolve the polymer to give the concentrations of 50 and 200 ppm. It was certified preliminarily that SANDEX–C had no effect on the drag reduction in a turbulent pipe flow.

2. Results

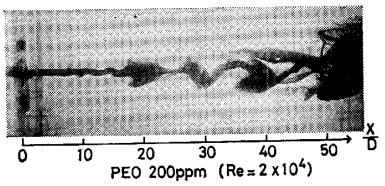
The results of flow visualization are shown in Fig. 2. The jets of coloured water of 50 and 200 ppm PEO solutions were injected into the fluid which was uncoloured but otherwise the same as injecting fluid. The striking suppression of small-scale turbulence is observed in the submerged jets of polymer solutions. The propagation of the polymer jet becomes smaller than that of Newtonian fluid. This fact enables us to assume that the turbulent diffusion in the submerged jet of polymer solution decreases considerably. This observation agrees with the results of Gadd[2] and Shulman et al.[9].



Water (Re = 2 x 10^4)



PEO 50ppm (Re = 2 x 10^4)



PEO 200ppm (Re = 2 x 10^4)

Fig. 2 Flow visualization of the submerged jets with and without polymer additive.

The variation of mean velocity along the jet axis was measured by a pitot tube and shown in Fig. 3. As already discussed by Smith et al.[8], the sensitivity of pitot tube measurement in viscoelastic fluids is poor. In this study, the read out of the pitot tube was calibrated by the known velocity of the same polymer solution. All the results of this work were obtained at $Re = 20000$. The length of potential core in the polymer solutions increases according to the increase of polymer concentration. The

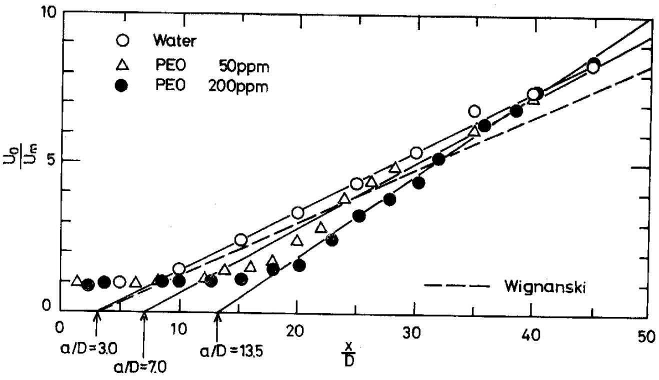


Fig. 3 Variation of the jet center-line velocity along the jet axis.

hypothetical origin of the jet, i.e. the "origin of similarity", was determined from Fig. 3. The distance between the origin of similarity and the jet outlet, indicated by a, is given in Table 1. The value of a in a Newtonian fluid coincides with that of Wignanski and Fiedler[12] whose data was taken at $x/D<50$. In the following discussion, the length scale of the jet would be referred to $x-a$, not x, to emphasize the similarity relationship of the jet.

As mentioned in the previous section, the fluctuating velocity in the longitudinal and radial direction was measured simultaneously at some different positions in the radial direction. The velocity data was obtained from cinefilm of about 3000 frames which correspond to the time of 5 sec. As the individual frame data involved considerable reading error of coordinates on a film motion analyzer, the data of 5 successive frames were averaged to give the instantaneous velocity at the middle frame time. In Fig. 4, the variation of cumulative velocity in axial direction both for water and a polymer solution are plotted against sampling time. The mean velocity on the jet center-line becomes almost constant after 5 sec. But this sampling time was found to be not enough for the intermittent region of the submerged jet. Thus the discussion of this paper was restricted only in the center region of the jet where the intermittency factor was almost unity.

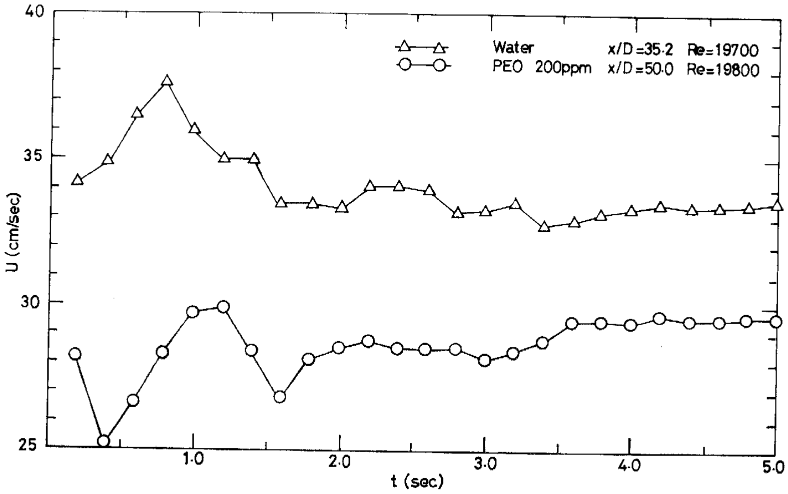


Fig. 4 Cumulative axial velocity on the jet center-line.

The mean velocity profiles in the axial direction are shown in Fig. 5. The solid line in this diagram is the experimental results obtained by Wignanski and Fiedler[12] for the case of Newtonian fluid. The results of water in this study show a little higher value than that of Wignanski and Fiedler. The difference between Wignanski and this work may be attributed to the experimental apparatus factor. More precise discussion of this difference is not possible at the present stage. In the case of polymer solutions, the propagation of jet decreased according to the increase of polymer concentration. This means that the eddy diffusivity in polymer solutions becomes smaller than the value of Newtonian fluid.

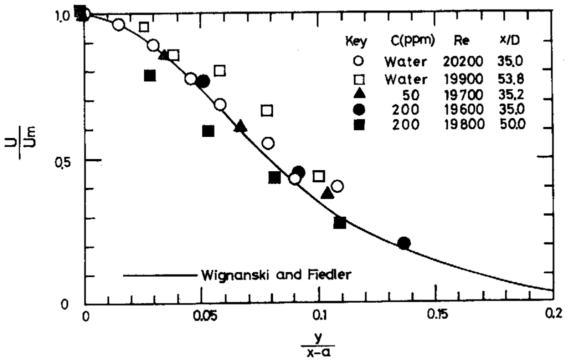


Fig. 5 Mean velocity profile in the axial direction.

Turbulent intensities in axial and radial directions are shown in Fig. 6 and Fig. 7 respectively. The results of water in this study show the same behavior as the experimental results of Wignanski and Fiedler[12] which are indicated by solid lines in both diagrams. The turbulent intensities of polymer solutions both in x and y direction show a significant decrease. The decrease of v' fluctuation is especially remarkable in the central portion of jet. This implies that the effect of polymer additive on the turbulent eddy is not isotropic in a submerged jet. The fluctuating velocities in x and y directions were measured simultaneously, so the distribution of Reynolds stress was able to be calculated. Results are shown in Fig. 8. The scatter of the experimental

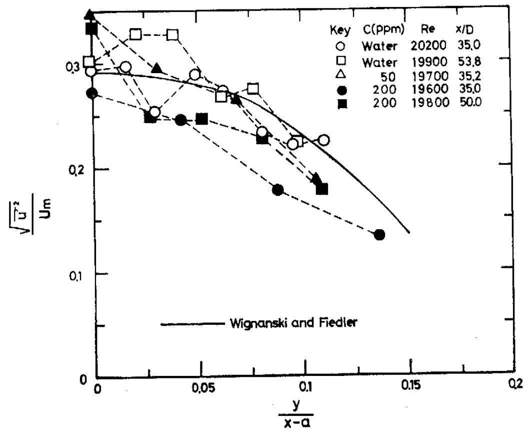


Fig. 6 Intensity of u'-fluctuation across the jet.

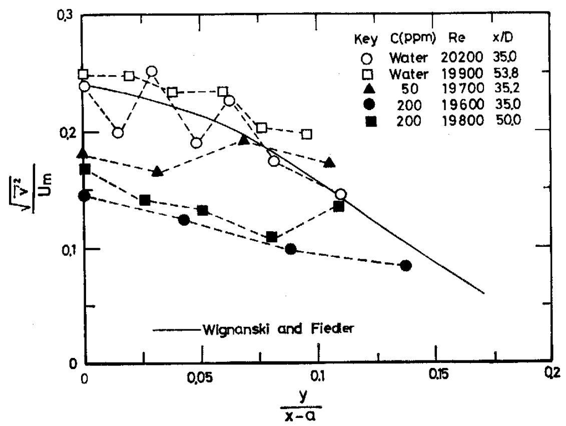


Fig. 7 Intensity of v'-fluctuation across the jet.

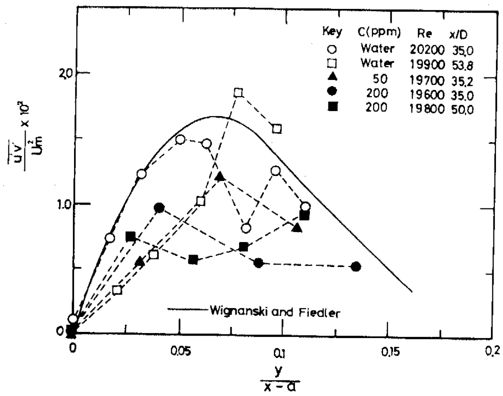


Fig. 8 Reynolds stress distribution across the jet.

results in this diagram is considerably large. This scatter was caused by the short sampling time of the film analysis. In any case, the drastic decrease of the Reynolds stress distributions in the polymer solutions is observed in this diagram. The decrease of eddy diffusivity in a turbulent pipe flow of the drag reducing fluids had already been found by the previous experiments[5]. The results shown in Fig. 8 certify that there exists a strong damping effect of polymer solution on the turbulent momentum transport of free jet.

The autocorrelation of the u' signal along the center-line of the jet was calculated according to the following definition.

$$R_E(T)=\frac{\overline{u'(t)u'(t-T)}}{\overline{u'^2}} \qquad (1)$$

Also the lateral space-correlation was obtained from the following definition.

$$R_{uu}(\Delta y)=\frac{\overline{u'(y)u'(y+\Delta y)}}{\sqrt{\overline{u'(y)^2}}\sqrt{\overline{u'(y+\Delta y)^2}}} \qquad (2)$$

In this experiments, the value of y in Eq. (2) was set to be equal zero. This means that in the calculation of the space-correlation one point was fixed on the jet center-line and the other point was moved in the radial direction. Δy indicates the distance between the two positions. The associated integral scale Λ_E and Λ_g were calculated from the correlation curves. It was pretty difficult to obtain the correct values of integral scales because of the scatter of the experimental results. Thus the following conventional approximations were adopted.

$$\Lambda_E=\int_0^{T_c} R_E(T)dT \qquad (3)$$

$$\Lambda_g=\int_0^{\Delta y_c} R_{uu}(\Delta y)d(\Delta y) \qquad (4)$$

T_c and Δy_c were defined to be equal to the position where the correlation curves crossed the zero level at the first time. This calculation was intended to give a rough estimation of the effect of the polymer additive on the structure of turbulence in the submerged jet. In the analysis of the autocorrelation, Taylor's hypothesis was adopted to calculate the value of the integral scale of longitudinal space correlation. For this calculation, the following equation was used.

$$\Lambda_f = U\Lambda_E \tag{5}$$

It had already been discussed that Taylor's hypothesis was basically invalid in the turbulent free jet[12]. Particularly this hypothesis fails near the edges of a submerged jet. The measuring points of this study were restricted only to the central part of the submerged jet where the intermittency factor was close to unity. Thus the determination of Λ_f using Taylor's hypothesis was expected to give a qualitative information about the effect of the polymer additive, although the applicability of Taylor's hypothesis was a little questionable.

The autocorrelation of the u' signal on the jet center-line is plotted in Fig. 9. The lateral space correlation is shown in Fig. 10. These diagrams show that the correlation

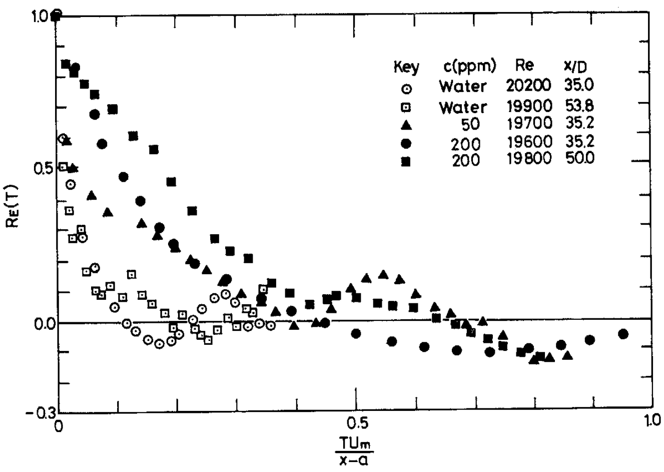


Fig. 9 Autocorrelation of the u' signal along the jet center-line.

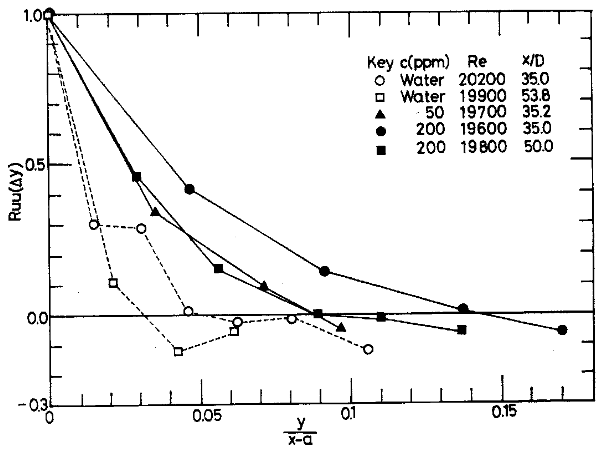


Fig. 10 Variation of the lateral correlation across the jet.

Table 1. Integral scales on the jet center-line.

	a [cm]	$\Lambda_g/(x-a)$	$\Lambda_f/(x-a)$	Λ_f/Λ_g
water	3.0	0.0168	0.0324	1.93
50 ppm	7.0	0.0319	0.0877	2.75
200 ppm	13.5	0.0414	0.1187	2.87
Wignanski and Fiedler	3.0	0.0157	0.0385	2.43

of the polymer solutions is stronger in the wide range of $TU_m/(x-a)$ or $\Delta y/(x-a)$ than the case of Newtonian fluid. The integral scales calculated by Eqs. (3), (4) and (5) are shown in Table 1. In this Table, the experimental results obtained by Wignanski and Fiedler[12] are also contained. The value of Reynolds number in their experiments was 10^5, and the data was taken at $x/D=30\sim90$. Assuming that the flow was self-preserving, the values of this experiments at $x/D=35$ and 50 were averaged to give this Table. It is obvious that the integral scale in the polymer solutions are greater than the case of Newtonian fluid. In the isotropic turbulence, the ratio, Λ_f/Λ_g, is equal to the value of 2[4]. The results of Newtonian fluid, both in this study and in the study of Wignanski and Fiedler, show that the value of Λ_f/Λ_g is almost equal to the value of 2. This means that the turbulence near the jet center-line is similar to the isotropic turbulence. In the case of polymer solutions, the values of Λ_f/Λ_g is bigger than that of Newtonian fluid flow. This means the representative eddy is stretched into the longitudinal direction.

The variation of Λ_f in the radial direction is plotted in Fig. 11. The broken line in this diagram is the experimental result of Wignanski and Fiedler[12]. The integral scale Λ_f of Newtonian fluid becomes greater according to the increase of the distance from the jet center-line. This tendency is just the same as the results obtained by Wignanski and Fiedler. The difference of the absolute values of Λ_f between the experimental results of this study and Wignanski and Fiedler seems to be caused by

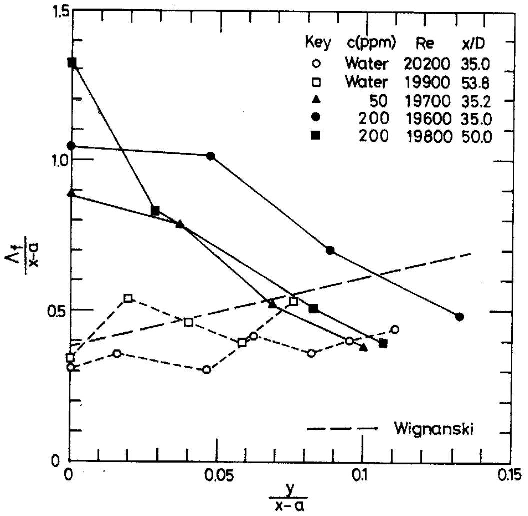


Fig. 11 Distribution of the longitudinal integral scale across the jet.

the Taylor's assumption in this study. Wignanski and Fiedler measured the longitudinal space correlation and calculated the value of Λ_f from the space correlation.

The behavior of the polymer solutions in the variation of Λ_f is quite different from that of Newtonian fluid. The maximum value of Λ_f was observed on the center-line of the submerged jet, and Λ_f seems to decrease according to the increase of y. This means that the effect of the polymer additive on the structure of turbulence appears most significantly in the central portion of the submerged jet, where the velocity gradient becomes zero. Most observations of turbulent pipe flow of the drag reducing fluid confirmed that the effect of polymer additive appeared in the wall region where the turbulent energy production showed a maximum value5,6,7). The interaction between the polymer additives and the turbulence has been thought to occur most significantly at the position where energy production had a maximum value. The experimental results of Wignanski and Fiedler in the submerged jet showed that the turbulence energy production had a maximum value at $y/x=0.052$ where the distribution of Reynolds stress showed a maximum value. They also showed that the dissipation had a maximum value on the jet center-line. The results shown in Fig. 11 mean that the suppression of turbulence caused by the polymer additive is not related to the turbulence production, but related more closely to the dissipation.

Conclusion

Turbulence measurement in the submerged jet of drag reducing polymer solutions were done by means of the analysis of the film photographed by a high-speed camera. Combining with the results of flow visualization, following conclusions were obtained.

1. Small scale turbulence in the submerged jet is significantly suppressed, and the integral scale of the polymer solutions is larger than that of Newtonian fluid.
2. Reynolds stress in the submerged jet shows the lower value in the case of polymer solution, and the jet propagation decreases dramatically.
3. The increase of the integral scale in the submerged jet of the polymer solutions is not isotropic. The eddy is stretched more significantly in the longitudinal direction.
4. Most significant effect of the polymer additive on the enlargement of the integral scale appears at the jet center-line, where the turbulent dissipation, not the turbulent production, has a maximum value.

Acknowledgement

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Nomenclature

a	position of the origin of similarity	[m]
c	concentration of polymer additive	[ppm]

D	nozzle diameter at the outlet section	[m]
Re	Reynolds number ($=U_0D/\nu$)	[—]
$R_E(T)$	autocorrelation coefficient	[—]
$R_{uu}(\Delta y)$	lateral space correlation coefficient	[—]
t	time	[sec]
T	delay time of autocorrelation	[sec]
U	time smoothed velocity in the x direction	[m/sec]
U_0	velocity at the nozzle outlet	[m/sec]
U_m	velocity on the jet center-line	[m/sec]
u'	fluctuating velocity in the x direction	[m/sec]
v'	fluctuating velocity in the y direction	[m/sec]
x	longitudinal coordinate in flow direction ($x=0$ corresponds to the nozzle outlet)	[m]
y	lateral coordinate ($y=0$ corresponds to the jet center-line)	[m]
Δy	distance between the two points where the space-correlation is taken	[m]
Λ_E	integral time scale defined by Eq. (3)	[sec]
Λ_f	longitudinal integral scale defined by Eq. (5)	[m]
Λ_g	lateral integral scale defined by Eq. (4)	[m]
ν	kinematic viscosity	[m^2/sec]

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