Decay of Temperature Variance in the Presence of Nonhomogeneous Strain

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The effect of nonhomogeneous strain caused by two-dimensional objects on single point statistical properties of the turbulent velocity and turbulent scalar (temperature) and their cross moments are investigated experimentally. The heated turbulent flow is produced by means of a biplane array of round rods and a biplane array of heated, thin wires placed downstream of the turbulence producing grid. The experiments are performed for three different ratios of the integral scale, L_0, to the object dimension, D, of 0.38, 1.90 and 3.1. Measurements of time resolved temperature and longitudinal and transverse velocity components are obtained using a triple wire probe consisting of a cold wire and two hot wires. Results indicate that, for $L_0/D = 1.9$ and 3.1, the decay rate of temperature variance is nearly the same in the region of maximum shear stress (mss) and near the centerline. However, the decay rate in these regions is less than the decay rate of the temperature variance outside the cylinder wake. For $L_0/D = 0.38$, the decay rates of temperature variance are the same in the regions of mss, near the centerline and outside the wake. Transverse growth of the wake is found to be either increased or nearly unchanged depending on, respectively, whether the free stream integral scale is larger or less than that of the wake.

1 Introduction

Mixing and dispersion of a turbulent passive scalar downstream of an object are of both fundamental and applied interest. For example, understanding of this type of flow is critical to the safe operation of fuel rods in nuclear reactors.

There have been numerous experimental and theoretical studies on mixing of temperature variance in the wake of a heated cylinder or unheated cylinder in a passively stratified field. Examples are, Durbin et al. (1982), Freymuth and Uberoi (1971), Alexopoulos and Keffer (1977), LaRue and Libby (1974), and Lumley (1975). However, in these studies, the effect of free-stream turbulence intensity or integral length scale on the mixing of the passive scalar has not been determined. The object of the present experimental study is to examine the simple case of mixing of a turbulent scalar in the wake of an unheated cylinder placed in a nearly homogeneous, isotropic and heated turbulent flow for different external turbulence intensities and integral scales.

2 Background

Symes and Fink (1977) study the effects of constant free-stream turbulence intensity of 3.5 percent with different axial integral length scales, on the unheated flow past cylinders. They use two different turbulence producing grids with mesh spacing of, respectively, 1.53 and 10 cm with grid Reynolds number of, respectively, 10^4 and 6.6×10^4. Cylinder Reynolds numbers are 0.67×10^4 and 1.35×10^4. Their results show that when the length scale of the external turbulence is larger than the diameter of the cylinder, the external turbulence causes a decrease in the mean defect velocity and axial (the term axial refers to the streamwise direction) integral length scales, an increase in the axial normal stress and wake half width and the moving equilibrium is reached at smaller axial distances than those of the conventional wake. However, when the length scale of the external turbulence is nearly the same as the diameter of the cylinder, the external turbulence has negligible effect on the wake flow.

Seely et al. (1975) study the effects of free stream turbulence of 7 and 10 percent on spheres by using the flash photolysis technique at Reynolds numbers based on sphere diameter of 700 and 3200. In their experiments, the level of background intensity is changed by changing the spacing between a turbulence producing grid and the sphere. Their results show that the size of the wake is progressively reduced with increasing free stream intensity. However, neither the position of the separation point, nor the attached boundary layer are affected by the background intensity. They conclude that free stream intensity causes enhancement of momentum transfer in the wake which results in smaller drag.

Zukauskas and Ziugzda (1985) study the effect of background intensity on the separation point of cylinders. Their results show that at the subcritical Reynolds number of 5.12×10^4, turbulence intensity of 0.5 percent does not change the

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location of the separation point which is found to be at 84 degrees. However, if the turbulence intensity is increased to 7 percent, separation moves slightly downstream to approximately 90 degrees.

At the near critical Reynolds number of 9.74×10^4, the shift in separation point is more pronounced where turbulence intensity of respectively 1.2, 3.5, and 9.9 percent causes the separation point to move to respectively 90, 100, and 120 degrees.

For the present study, the maximum Reynolds number is 18435 and the maximum intensity is 4.4 percent. Based on the results of Zukauskas and Ziugzda (1985), the separation point should be unaffected by changes in the free-stream intensity and any change in the transverse wake width and decay of turbulent temperature fluctuations will be due to the interaction of the free-stream and wake turbulence.

Alexopoulos and Keffer (1977) study the turbulent wake in a passively stratified field for different L_0/D ratios. They change the ratio, by changing the cylinder diameter. Thus the intensity at the cylinder remains a constant. Their results show that as the wake spreads laterally, the maximum temperature defect increases in the streamwise direction. There is also an increase in temperature variance in the downstream direction which they conclude is due to the presence of the mean temperature gradient. In their study no discussion is presented of the effect of different ratios of the free stream to wake integral scales on the decay of temperature variance.

Elghobashi and LaRue (1983) study the effect of mechanical strain on the dissipation of temperature variance and time scale ratio, r. Their study is limited to only one ratio of L_0/D with the main focus of the paper being the comparison of numerical predictions and experimental results of the dissipation and time scale ratio.

Additional related studies of the effect of strain on a turbulent scalar field include those of Mills and Corrsin (1959) and Warhaft (1980). Mills and Corrsin (1959) present results of an experimental study of the effect of a contraction with a 4:1 area ratio on temperature fluctuations which are generated by heating a turbulence producing grid, placed upstream of the contraction. In their study the root mean squared, rms, temperature fluctuations in the strained flow are compared to those obtained in the unstrained flow. The results show that contraction accelerates the decay of temperature fluctuations.

Warhaft (1980) also uses a symmetrical contraction with an area ratio of 4:1 to study the effect of a contraction on a passive scalar. Rather than using the turbulence producing grid to heat the flow, another grid (mandoline) made of fine, parallel horizontal wires is electrically heated to produce the temperature fluctuations. By heating different sets of wires in the mandoline, the initial scale size of the thermal fluctuations and hence the mechanical to thermal time scale ratio, r, can be varied. His results show that when r is greater than one, the contraction accelerates the thermal fluctuation decay rate, which does not approach a constant value. However, when r is less than one, the thermal fluctuation decay rate does not change. When $r \sim 1$, the thermal length scale increases by an amount equal to the contraction ratio.

3 Experimental Arrangement

The measurements discussed herein are carried out in the UCI low speed, closed circuit wind tunnel which has a cross section of 60×90 cm and a background intensity of about 0.06 percent. Figure 1 shows the arrangement of the flow field and the axial development of turbulence intensity and integral length scale of the external flow. Here, X_0 is measured from the turbulence producing grid.

The turbulent velocity fluctuations are produced by one of two square mesh, biplane grids consisting of either 0.476 or 0.95 cm polished, round aluminum rods with mesh spacing, M_u, respectively, of 2.54 or 5.08 cm. The solidity for both grids, which are placed 97.80 cm downstream of the contraction, is 0.34. The nominal mean velocity is 9 m/s which corresponds to grid Reynolds numbers of about 14,750 and 29,500.

Heat is introduced into the flow by means of a biplane grid of chromel-p heater wires of 0.254 mm dia with a mesh spacing of 1.27 cm which is placed 46 cm downstream of the turbulence-

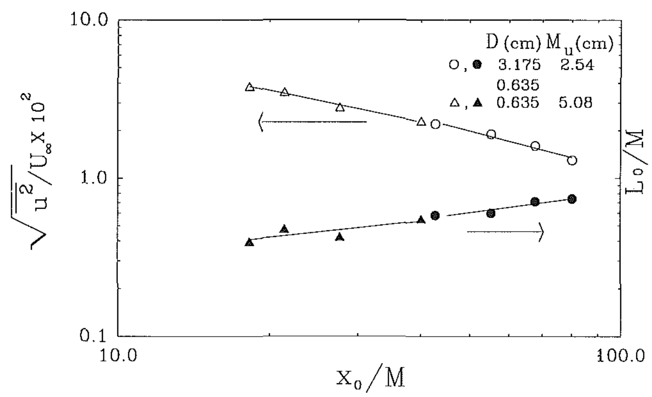

Fig. 1 Flow configuration and streamwise development of turbulence intensity and integral length scale of the external flows. (Uncertainty in $\sqrt{\overline{u^2}} \times 10^2/U_\infty = \pm 0.02$, in $X_0/M = \pm 0.1$, and in $L_0/M = \pm 0.05$ at 20:1 odds.)

Table 1

D (cm)	Re_D	M_u (cm)	$L_0^{1,2}/D$	$\overline{u^2}^{1/2,2}/U_\infty$
0.635	3687	2.54	3.1	0.027
0.635	3687	5.08	1.9	0.044
3.175	18435	5.08	0.38	0.044

1. The integral scale is obtained using the variance of the time derivative and the axial turbulent velocity, Taylor's hypothesis and the assumption of local isotropy as $L_0 = \overline{u^2}^{3/2}/\epsilon_u$ where $\epsilon_u = 15\nu\overline{(\partial u/\partial x)^2}$ (cf. Tennekes and Lumley (1972)).
2. Evaluated in the free stream at the downstream location of the cylinder.

Nomenclature

- L_0 = integral length scale (cm)
- M_u = mesh spacing (cm)
- $\overline{q^2}$ = twice the turbulent kinetic energy (m^2/s^2)
- Re = Reynolds number, $\rho U_\infty D/\nu$, $\rho U_\infty M_u/\nu$
- r = time scale ratio
- U_∞ = free-stream velocity (m/s)
- $U_{d\max}$ = maximum defect velocity m/s
- $\overline{u^2}^{1/2}$ = streamwise turbulent velocity m/s
- S = spreading parameter
- X_0 = distance from turbulence producing grid (cm)
- $Y_{1/2}$ = half width (cm)
- ϵ_u = dissipation rate of kinetic energy (m^2/s^3)
- ϵ_θ = dissipation rate of temperature variance (C^2/s)
- Θ = momentum thickness (cm)
- $\overline{\theta^2}$ = temperature variance (C^2)
- ν = kinematic viscosity (m^2/s)
- ρ = density (kg/m^3)
- ΔT = mean temperature difference, 0.55 C

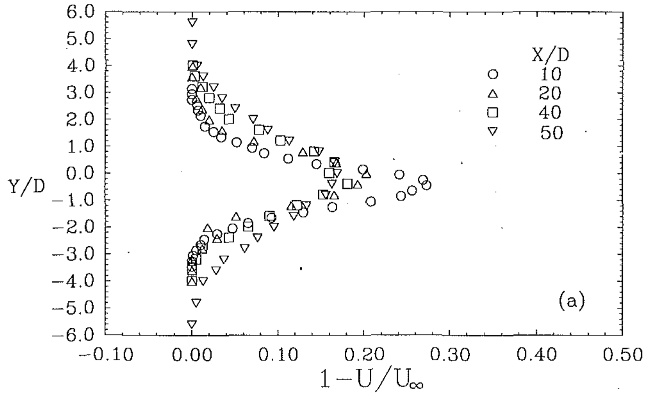

Fig. 2(*a*)

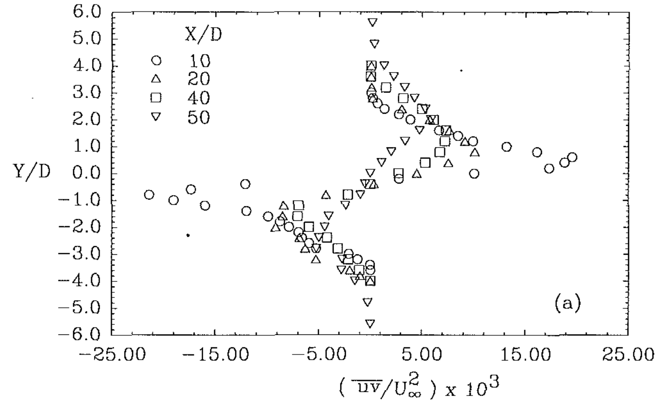

Fig. 3(*a*)

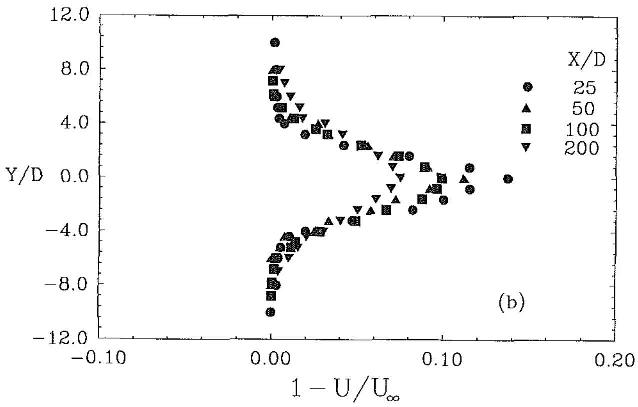

Fig. 2(*b*)

Fig. 2 Transverse variation of the mean defect velocity for experiments with (*a*) L_0/D = 0.38, and (*b*) L_0/D = 3.1. (Uncertainty in L_0/D = ±0.05, in Y/D = ±0.01, and in U/U_∞ = ±0.005 at 20:1 odds.)

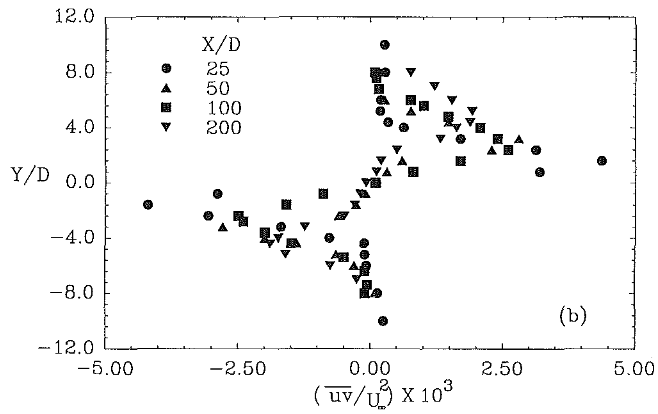

Fig. 3(*b*)

Fig. 3 Transverse variation of the turbulent shear stress for experiments with (*a*) L_0/D = 0.38, and (*b*) L_0/D = 3.1. (Uncertainty in $\overline{uv} \times 10^3/U_\infty^2$ = ±0.25 at 20:1 odds.)

producing grid (all wires are heated during the experiment). The solidity of the grid is 0.04. The grid is electrically heated and a power dissipation of 2.7 kW leads to a 0.55°C rise in the mean temperature across the grid. The corresponding mean temperature is uniform and constant both upstream and downstream of the cylinder.

The two dimensional wake flow is produced using polished aluminum cylinders which are placed 31 cm downstream of the heater wires and at the center plane of the tunnel. The dimensions of the cylinders and corresponding grids and flow characteristics are presented in Table 1.

Simultaneous time-resolved measurements of the streamwise and transverse velocities (u, v) and temperature (θ) are obtained using a triple-wire probe consisting of two hot wires in the "x" configuration and a cold wire mounted normal to the plane of the hot wires and 0.75 mm upstream of their projected intersection. The hot wires are platinum-plated tungsten which are 5 μm in diameter and 1.2 mm in length. The overheat ratios are 1.7. The cold wire is platinum with a diameter of 0.625 μm and a length of 0.75 mm.

The hot wires and the cold wire are operated respectively by two TSI Model 1050 constant temperature anemometers and a fast-response a.c. temperature bridge. The cold wire is supplied with a constant current of 180 μA which makes it's sensitivity to velocity insignificant (cf. LaRue et al. (1975)). The probe is directly calibrated for velocity and temperature and flow direction in the ranges of respectively, 3 to 9 m/s, 17 to 23 C and ±20 degrees. The frequency response of the hot wires determined using the square wave technique is 16 kHz and that of the cold wire is estimated to be about 4 kHz (cf. LaRue et al. (1975)).

Voltages and voltage derivatives from the constant temperature anemometers and the a.c. bridge are recorded by means of an FM tape recorder on analog magnetic tape at a tape speed of 38.1 cm/s, which correspond to a maximum frequency response of 5 kHz. Signals are then low-pass filtered at 3 kHz and digitized at the AMES department of the University of California, San Diego by means of a Phoenix Analog to Digital converter with 16-bit resolution at a rate of 6000 samples/sec-channel. At each probe position 90 records consisting of 4096 samples/channel which correspond to 31.7 sec of data and more than one hundred thousands data sextets are digitized. Digitized data are analyzed using a DEC LSI-11/73 micro computer and standard software.

4 Results and Discussions

Figures 2 to 4 show transverse variations of the mean defect velocity, shear stress and temperature variance at different downstream locations for experiments with L_0/D = 0.38 and 3.1. On the centerline at X/D = 50, the normalized mean defect velocities for L_0/D = 0.38 and 3.1 are 0.16 and 0.11 respectively. The free-stream intensities at this location is approximately 1.5 and 3.5 percent, respectively. Clearly, the momentum transport from the free stream into the wake is increased when the integral scale in the free stream is larger than that in the wake. Application of a simple eddy viscosity model would suggest that the shear stress would be reduced for the flow with L_0/D = 3.1 as compared to that for L_0/D = 0.38. This is consistent with the results shown on Figs. 3(*a*) and 3(*b*). There it can be seen that the maximum normalized turbulent shear stress is reduced at $X/D = 50$, from about 6×10^{-3} for $L_0/D = 0.38$ to about 2.75×10^{-3} for $L_0/D = 3.1$.

The temperature variance profiles decrease in the wake similar to the mean velocity profiles and reach a minimum at the center line. The decrease in temperature fluctuation is at least in part due to heat transfer between the fluid and the cylinder. The cylinder temperature is equal to the mean temperature of the flow. Thus, the temperature difference of fluid which passes near the cylinder and the mean temperature will be reduced. This leads to a reduction in temperature variance on the centerline of the wake. The temperature difference of fluid which passes closer to the cylinder surface is reduced more than the temperature difference of fluid particles which pass further away from the cylinder surface. It seems reasonable to assume that fluid which pass close to the cylinder surface will have a higher probability of arriving near the wake centerplane than those fluids which pass further away from the cylinder surface. Consequently the temperature variances will be reduced more on the centerplane than at other positions in the wake.

Figure 5(*a–d*) show axial variations of the maximum mean defect velocity, $U_{d\max}$, momentum thickness, Θ, wake half-

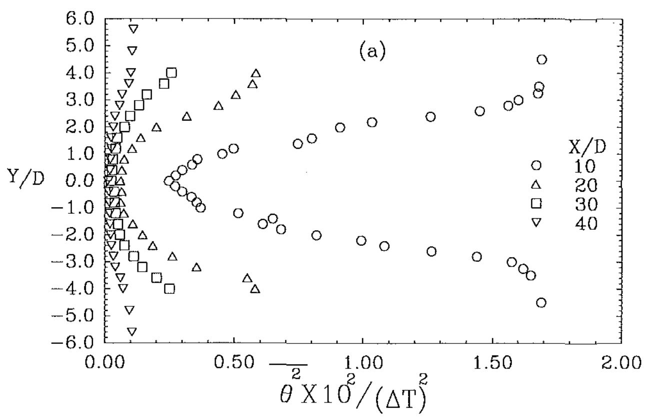

Fig. 4(*a*)

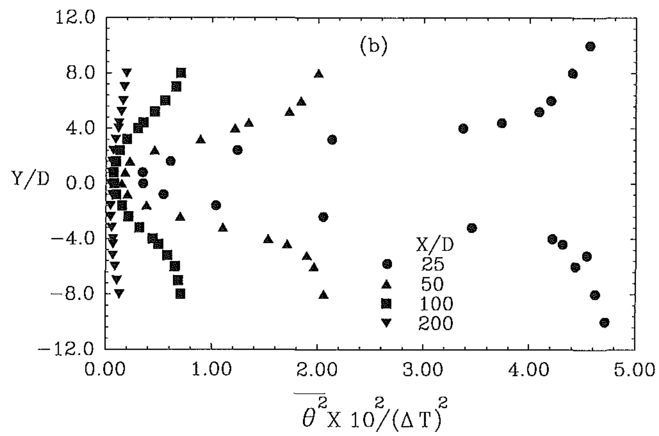

Fig. 4(*b*)

Fig. 4 Transverse variation of the temperature variance for experiments with (*a*) $L_0/D = 0.38$, and (*b*) $L_0/D = 3.1$. (Uncertainty in $\overline{\theta^2} \times 10^2/(\Delta T)^2 = \pm 0.075$ at 20:1 odds.)

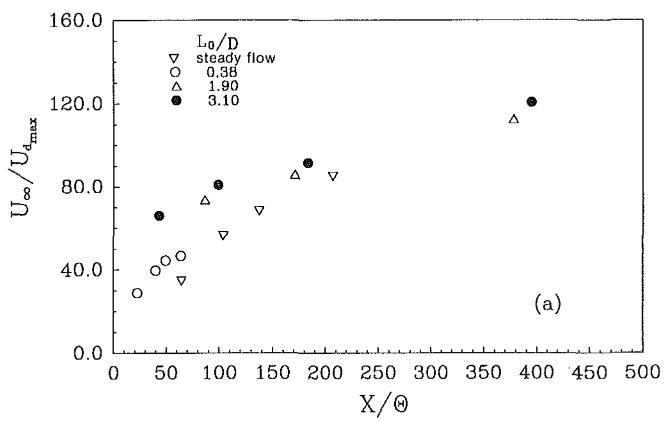

Fig. 5(*a*)

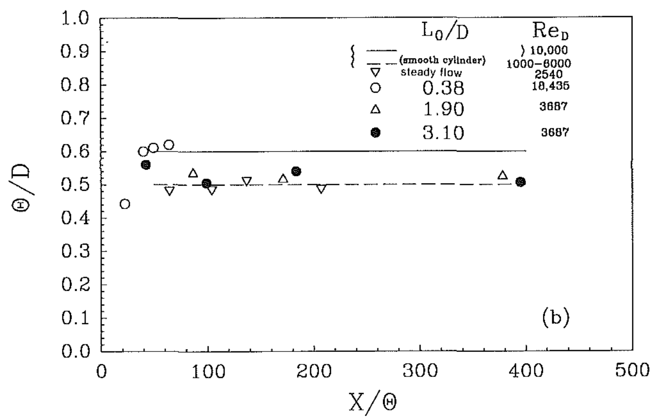

Fig. 5(*b*)

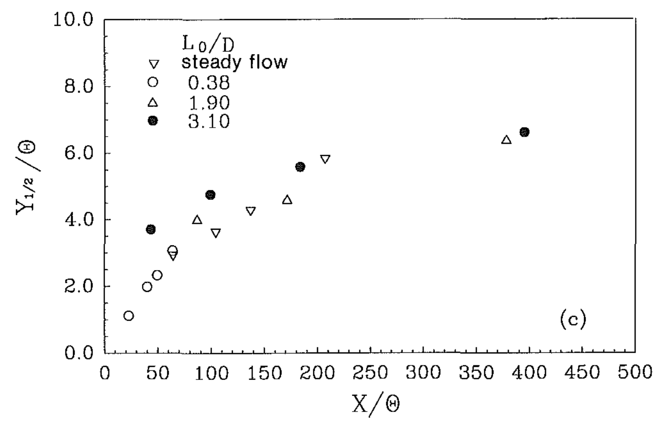

Fig. 5(*c*)

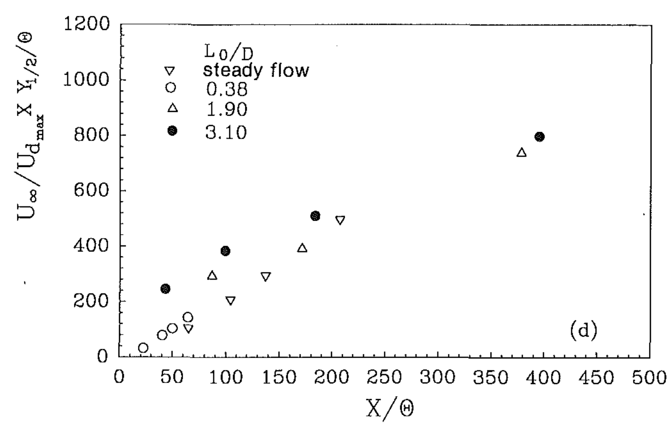

Fig. 5(*d*)

Fig. 5 Streamwise development of (*a*) mean defect-velocity scale, (*b*) wake momentum thickness, (*c*) wake half-width, and (*d*) spreading parameter. (Uncertainty in $U_\infty/U_{d\max} = \pm 0.005$, in $\Theta/D = \pm 0.03$, in $Y_{1/2}/\Theta = \pm 0.05$, in $X/\Theta = \pm 5$ at 20:1 odds.)

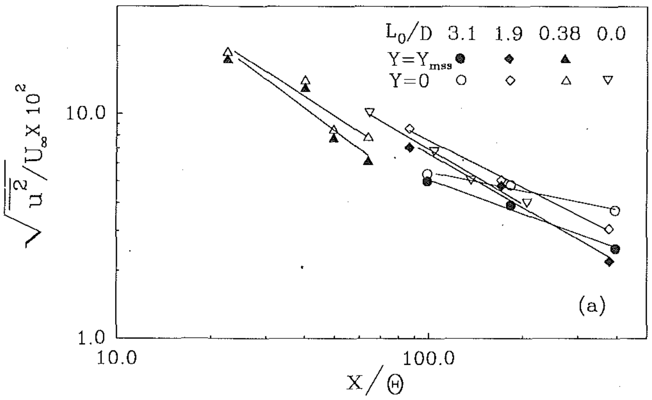

Fig. 6(*a*)

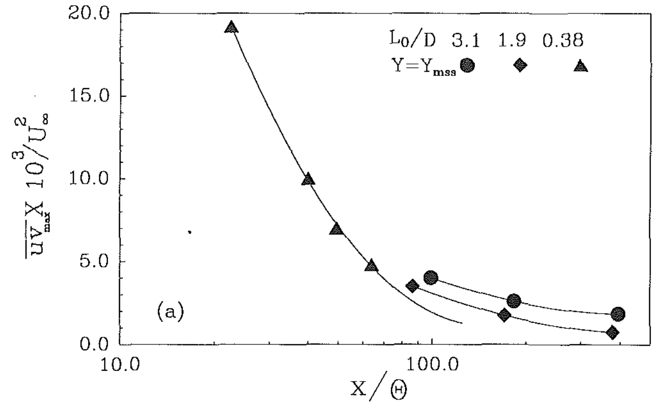

Fig. 7(*a*)

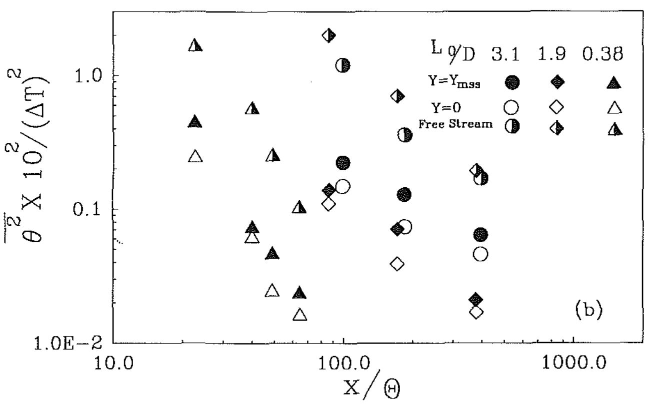

Fig. 6(*b*)

Fig. 6 Streamwise development of (*a*) turbulence intensity, and (*b*) temperature variance

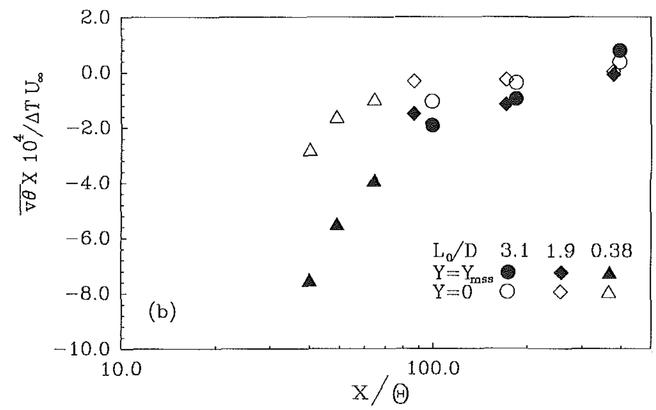

Fig. 7(*b*)

Fig. 7 Streamwise development of (*a*) maximum shear stress, and (*b*) transverse heat flux

width, $Y_{1/2}$, and spreading parameter, S, for experiments with different L_0/D ratios. The momentum thickness is obtained by integrating the wake profiles. The half-width is the transverse distance where the mean defect velocity is half of its maximum value, and the spreading parameter is given by Townsend (1976) as:

$$\frac{S}{\Theta}=\frac{1}{2}\frac{d}{dX}\left(\frac{U_\infty}{U_{d\max}}\times\frac{Y_{1/2}}{\Theta}\right) \quad (1)$$

For experiments with $L_0/D = 0.38$ and for $X/\Theta \leq 40$, where there exist an axial pressure gradient due to the presence of the cylinder, the momentum thickness increases in the downstream direction. However, for $X/\Theta > 40$, the momentum thickness is relatively constant and any variation is due to experimental uncertainty. Figure 5(*b*) also shows the variation of momentum thickness for a smooth cylinder, placed in a uniform flow for different Reynolds number regimes, obtained from Schlichting (1979) and from results obtained as part of the present study. The experimental results with different L_0/D ratios agree with the corresponding results for cylinders in uniform flow. This indicates that the free-stream turbulence does not change the location of the separation point. Thus, any enhancement in the mixing of turbulence is due to the interaction of the large scale structures.

The interaction can be characterized by the ratio of the free stream integral scale to the corresponding integral scale in the wake. The integral scale in the wake is approximately equal to the mixing length (cf. Tennekes and Lumley (1972)) which has an average value of $0.4Y_{1/2}$ (cf. Hinze (1959)). At $x/d = 50$, the ratios of free-stream integral scale to the corresponding average integral scale in the wake are, respectively, 0.61 and 3.58 for $L_0/D = 0.38$ and 3.10. For $L_0/D = 0.38$, the half wake width, velocity defect and spreading parameter are unaffected by the free stream turbulence. In contrast for $L_0/D = 3.10$, where the free-stream integral scale is about twice that of the wake, the half wake width is increased, the velocity defect is decreased and the spreading rate is increased.

Figure 6(*a*) shows the axial decay of turbulence intensity in the wake, in the regions of mss and near the centerline along with the corresponding results for a smooth cylinder placed in a uniform flow. For all L_0/D ratios, the turbulence intensity decays faster in the region of mss than near the center line. For $L_0/D = 0.38$, near the center line, the decay rate is nearly the same as the corresponding value for the smooth cylinder in a uniform flow. In addition, when $L_0/D = 0.38$, the decay rate is higher in both regions than when $L_0/D = 1.9$ and 3.1. Symes and Fink (1977) show that when $L_0/D > 1$, the external turbulence causes an increase in the wake turbulence intensity. In their study as for the present study when $L_0/D = 0.38$ and 1.9, the free stream intensity is maintained constant. Comparisons of the decay rate in both regions of mss and near the center line for these two conditions, consistent with Symes and Fink (1977), show that the turbulence intensity increases with increasing values of L_0/D.

Figure 6(*b*) shows the axial decay of temperature variance. The decay rates are estimated using the method of least squares, to determine the values of A and n in the expression $\overline{\theta^2}/(\Delta T)^2 = AX^{-n}$. For experiments with $L_0/D = 3.1$ and 1.9, the decay rates are nearly the same in the region of mss and near the center line. However, these decay rates are less than the corresponding value outside the wake.

The decay rate of temperature variance increases with decreasing values of L_0/D, and for $L_0/D = 0.38$, the decay rate of temperature variance is the same in regions of mss, near the centerline and outside the wake. This increase in the decay rate with decreasing L_0/D ratio corresponds to higher shear stress that exists for flows with small values of L_0/D.

Figure 7(*a*) shows downstream variation of the maximum shear stress for experiments with different L_0/D ratio. The values are taken from the regions of positive shear stress. Results show that the maximum shear stress increases with increasing values of L_0/D.

Figure 7(*b*) shows downstream variation of the transverse heat flux in the regions of mss and near the center line. The values for the transverse heat flux correspond to the regions of positive shear stress. The heat flux is negative in all regions except far downstream where they approach small positive values. For all L_0/D ratios, the heat flux is higher in magnitude in the region of mss than near the center line. In addition, in both regions of mss and near the center line, the heat flux is not significantly affected by the different values of L_0/D.

5 Conclusion

The effects of different background intensities with different integral length scales on the decay rate of the temperature variance and wake velocity statistics are experimentally investigated. Results show that when $L_0/D > 1$, the maximum mean defect velocity decreases and the wake half-width increases with increasing L_0/D.

The decay rates of turbulence intensity and temperature variance for experiments with $L_0/D < 1$ are larger than the corresponding values for experiments with $L_0/D > 1$.

For experiments with $L_0/D > 1$, the decay rate of turbulence intensity and temperature variance are higher in the region of mss than near the centerline. In addition, in both regions, the decay rates are less than the corresponding values outside the wake. However, when $L_0/D < 1$, the decay rate of temperature variance is the same in regions of mss, near the centerline and outside the wake.

References

Alexopolous, C. C., and Keffer, J. F., 1977, "Turbulent Wake in a Passively Stratified Field," *Phys. of Fluids*, Vol. 14, No. 2, pp. 216–224.

Durbin, P. A., Hunt, J. C., and Firth, D., 1982, "Mixing by a Turbulent Wake of a Uniform Temperature Gradient in the Approach Flow," *Phys. of Fluids*, Vol. 25, No. 4, pp. 588–591.

Elghobashi, S., and LaRue, J. C., 1983, "The Effect of Mechanical Strain on the Dissipation Rate of Scalar Variance," *Fourth Symposium of Turbulent Shear Flow*, Karlsruhe, Germany.

Freymuth, P., and Uberoi, M., 1971, "Structure of Temperature Fluctuations in the Turbulent Wake Behind a Heated Cylinder," *Phys. of Fluids*, Vol. 14, No. 2, pp. 2574–2580.

Hinze, J. L., 1959, *Turbulence*, McGraw-Hill, New York, p. 507.

LaRue, J. C., Deaton, T., and Gibson, C. H., 1975, "Measurement of High-Frequency Turbulent Temperature," *Rev. Sci. Instrum.*, Vol. 46, No. 6, pp. 757–764.

LaRue, J. C., and Libby, P. A., 1974, "Temperature Fluctuations in a Plane Turbulent Wake," *Phys. of Fluids*, Vol. 17, No. 11, pp. 1956–1967.

Lumley, J. L., 1975, "Modeling Turbulent Flux of Passive Scalar Quantities in Inhomogeneous Flows," *Phys. of Fluids*, Vol. 18, No. 6, pp. 619–622.

Mills, R. R., and Corrsin, S., 1959, "Effect of Contraction on Turbulence and Temperature Fluctuations Behind a Heated Grid," NACA Memo 5-5-59W.

Schlichting, H., 1979, *Boundary Layer Theory*, 7th ed., McGraw-Hill, New York.

Seely, L. E., Hummel, R. L., and Smith, J. W., 1975, "Some Observations of the Wake Behavior in Laminar and Turbulent Free Stream Flow," *4th Symposium on Turbulence in Liquids*, University of Missouri, Rolla, pp. 289–301.

Symes, C. R., and Fink, L. E., 1977, "Effects of External Turbulence Upon the Flow Past Cylinders," *Proceeding of the Symposium on Structure and Mechanisms of Turbulence*, Technische Universitat Berlin, pp. 86–101.

Tennekes, H., and Lumley, J. L., 1972, *A First Course in Turbulence*, MIT Press, Boston, Mass., p. 45.

Townsend, A. A., 1976, *The Structure of Turbulent Shear Flow*, Cambridge University Press, 2nd edition.

Warhaft, Z., 1980, "An Experimental Study of the Effect of Uniform Strain on Thermal Fluctuations in Grid-Generated Turbulence," *J. Fluid Mech.*, Vol. 99, pp. 545–573.

Zukaskas, A., and Ziugzda, J., 1985, *Heat Transfer of a Cylinder in Cross Flow*, Hemisphere Publishing Corporation.