Int. J. Heat Mass Transfer. Vol. 28, No. 8, pp. 1461–1468, 1985
Printed in Great Britain

0017-9310/85 $3.00 + 0.00

Turbulent Prandtl number and spectral characteristics of a turbulent mixing layer

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(*Received* 16 *January* 1984 *and in final form* 28 *January* 1985)

Abstract—Measurements have been made of all three velocity fluctuations and of the temperature fluctuations in a thermal mixing layer associated with a turbulent plane jet. In a region of the flow for which the Reynolds stresses and heat fluxes are large, the turbulent Prandtl number is equal to about 0.4. The small magnitude of the turbulent Prandtl number in the present and other mixing layer investigations seems to reflect the relatively strong coherence of the flow. Spectra and cross spectra of velocity and temperature fluctuations exhibit a pronounced peak at the average frequency of the coherent motion. A close similarity is noted between the spectrum of the lateral velocity fluctuation and the temperature spectrum.

1. INTRODUCTION

VALUES of the turbulent Prandtl number Pr_t in the range of about 0.5 to about 1 have been reported in the literature in the fully turbulent region in shear flows. Mayer and Divoky's [1] tabulation of Pr_t values in plane and axisymmetric turbulent jets and wakes indicated a range of 0.42–0.83. General consensus (e.g. Launder [2]) suggests a turbulent Prandtl number which is only slightly smaller than 1.0 for the logarithmic region of a turbulent boundary layer. Fiedler [3] commented that the difference in Pr_t for different flows or for different locations within a single flow was not fully understood. With the aim of finding a model for the transport mechanism of a scalar quantity, in a typical turbulent shear flow, Fiedler [3, 4] investigated a slightly heated two-dimensional shear layer and observed that the transport of heat was primarily due to a large scale vortical motion. A value of Pr_t of about 0.3 in the almost fully turbulent region of this flow can be inferred (details will be given later) from the data of Fiedler [3, 4] and Wygnanski and Fiedler [5]. Townsend [6] proposed a variation of Pr_t as a function of the total strain characterising a particular flow but the minimum value of Pr_t indicated by his scheme is 0.4. It should be noted that many studies, either experimental or of a theoretical or modelling nature (e.g. [7]–[19] to mention only a few), have addressed various aspects of the organised motion in the mixing layer. A recent review by Hussain [20] of coherent structures in turbulent shear flows has also dealt with both natural and forced mixing layers. The previous studies have contributed valuable information on the organised motion but further work is required to firmly quantify the contributions that coherent structures make to the momentum and heat transport, especially when the influence of different initial and boundary conditions are taken into account.

The implication from the above considerations that the turbulent diffusivity of heat may be significantly larger than that of momentum in a two-dimensional mixing layer reflecting the possible influence of the large scale motion provided the major motivation for the present investigation. Measurements were made in a slightly heated turbulent mixing layer with a view to determine Pr_t and ascertain the possible influence of the large scale motion. In particular, spectra and cross spectra of velocity and temperature fluctuations are presented in an attempt to shed some light on the apparent disparity between transport mechanisms for momentum and heat.

2. EXPERIMENTAL ARRANGEMENT

The experimental mixing layer investigated here is one of the two mixing layers associated with the near field of a plane jet. The experimental facility has been described in Antonia *et al.* [21]. It is sufficient to recall that the jet issues from a vertical slot of width $d = 12.7$ mm and aspect ratio 20. A 20 : 1 contraction connected the nozzle to the settling chamber. The jet is heated by 1-kW electrical coil elements located downstream of the blower exit.

Measurements were made at a nominal jet exit velocity U_j of 9 m s^{-1} and a Reynolds number $R_d = U_j d/\nu = 7600$. The jet temperature was maintained at a nominal value T_j of 25°C. Velocity fluctuations u and v were measured, at the same time as the temperature fluctuation θ, with an ×-probe/cold wire

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NOMENCLATURE

B	non-dimensional parameter, $(\overline{q^2}/\overline{\theta^2})^{1/2}(\partial T/\partial y)/(\partial U/\partial y)$
$Co_{\alpha\beta}(f)$	co-spectrum of fluctuations α and β such that $\int_0^\infty Co_{\alpha\beta}(f)\,df = \rho_{\alpha\beta}$
$Coh_{\alpha\beta}(f)$	spectral coherence of fluctuations α and β, $(Co^2_{\alpha\beta}+Q^2_{\alpha\beta})/F_\alpha F_\beta$
$\widehat{Coh}_{\alpha\beta}$	maximum value of $Coh_{\alpha\beta}(f)$
d	nozzle width
d_w	diameter of cold wire
F_α, F_β	spectral density of α, β ($\equiv u, v, w$ or θ) defined such that $\int_0^\infty F_\alpha(f)\,df = 1$
F_q	spectral distribution corresponding to $\overline{q^2}$, defined such that $\overline{q^2}F_q(f) = \overline{u^2}F_u(f)+\overline{v^2}F_v(f)+\overline{w^2}F_w(f)$ and $\int_0^\infty F_q(f)\,df = 1$
f	frequency [Hz]
Pr_t	turbulent Prandtl number, $(\overline{uv}/\overline{v\theta})(\partial T/\partial y)/(\partial U/\partial y)$
$Q_{\alpha\beta}$	quadrature spectrum between α and β
$\overline{q^2}$	twice the turbulent kinetic energy per unit mass ($\equiv \overline{u^2}+\overline{v^2}+\overline{w^2}$)
R_d	Reynolds number $U_j d/\nu$, based on exit velocity
T	local mean temperature, relative to ambient
u, v, w	velocity fluctuations in x, y, z directions
$\overline{uv}$	kinematic Reynolds shear stress
$\overline{u\theta}$	thermometric longitudinal heat flux
U	local mean velocity
$\overline{v\theta}$	thermometric lateral heat flux
x	distance measured from the nozzle exit plane
y	coordinate along the lateral or main shear direction. Its origin 0 is at the nozzle lip
z	spanwise coordinate.

Greek symbols

η	non-dimensional similarity coordinate, y/x
θ	temperature fluctuation
$\overline{\theta^2}$	temperature variance.

Subscripts and other symbols

j	refers to value at nozzle exit
$\overline{}$	conventional time average.

arrangement at only two streamwise stations ($x/d = 4, 5$). The ×-wires (5-μm diameter Pt–10% Rh, 0.6-mm length) were mounted in the x–y plane and were separated by about 0.5 mm. A 0.63-μm cold wire (Pt–10% Rh, 0.6-mm length) was located 0.5 mm upstream of the centre of the ×-probe and orthogonally to the ×-probe plane. The ×-wires were operated with constant temperature anemometers at a resistance ratio of 1.8. The cold wire was operated in a constant current (0.1 mA) circuit. Cursory traverses were made at $x/d = 2.5, 3, 3.5, 4$ with a single 0.63-μm cold wire (Pt–10% Rh, 0.6-mm length) primarily to obtain temperature statistics in the outer (low speed) part of the mixing layer uncontaminated by the thermal wakes of the ×-wires when flow reversal* occurs. Fluctuations u and w were also measured in the unheated flow with the ×-probe mounted in the x–z plane.

The ×-probe was calibrated for speed and yaw (in the range ±25°) at the jet exit plane. The temperature coefficient of sensitivity of the cold wire was determined, with the wire mounted at the jet exit, using the method described in [21]. The 'high' and 'low' frequency responses of the cold wire were checked by measurement [23] and with the use of the criterion developed in [24], respectively. For the present experimental conditions no compensation of the wire thermal inertia was necessary and wire end effects were sufficiently small to be neglected. Signals from the ×-probe and cold wire were recorded on an FM tape recorder and subsequently digitised on a PDP 11/34 computer. For spectral measurements, each signal was low-pass filtered at 2 kHz and sampled at 4 kHz. The temperature contamination of the wire signals was removed prior to linearisation, both operations being carried out on the computer.

At the nozzle exit, the boundary layers are laminar with a mean velocity distribution in close agreement with the Blasius solution. The Reynolds number based on the boundary-layer momentum thickness was approx. 140 while the longitudinal rms turbulence level was about 0.2% at the centre of the nozzle exit plane.

*Flow reversal was first detected using a technique similar to that in [22] at $\eta \simeq 0.08$. Accordingly, temperature statistics obtained with the single cold wire and with the cold wire next to the ×-probe differed for $\eta \gtrsim 0.08$.

3. TURBULENT FLUXES AND PRANDTL NUMBER

Mean velocity and mean temperature profiles measured at $x/d = 4$, 5 are plotted in Fig. 1 using similarity variables. Kinematic Reynolds shear stress and lateral heat flux distributions are shown in Figs. 2

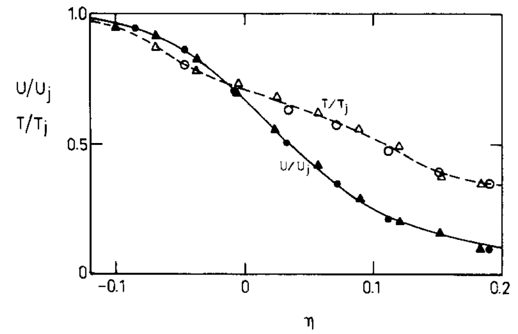

FIG. 1. Mean velocity and temperature profiles. U/U_j: ●, $x/d = 4$; ▲, $x/d = 5$. T/T_j: ○, $x/d = 4$; △, $x/d = 5$.

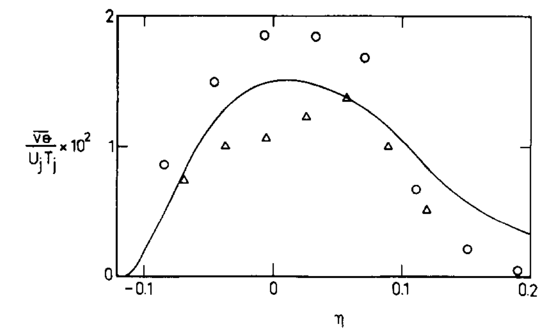

FIG. 3. Lateral heat flux distributions. Measured: ○, $x/d = 4$; △, $x/d = 5$. Calculated assuming self-preservation: ——.

and 3, respectively. Although it is difficult to draw definite conclusions about self-preservation on the basis of measurements at only two values of x, the most that can be said from the results in Figs. 1 and 2 is that they are not inconsistent with the notion of self-preservation. The shear stress distributions are nearly identical at the two stations as are the normal stresses (not shown here). Correlation coefficients between u and v and also u and θ at $x/d = 4$ were also in good agreement with those at $x/d = 5$. There is a significant difference however between distributions of $\overline{v\theta}/U_j T_j$ at the two stations. Mean velocity and temperature distributions measured on the jet centreline and schlieren photographs of the flow such as that shown in Fig. 4 indicated that the end of the potential core occurs between $x/d = 4$ and $x/d = 5$. Measurements [25] in the interaction region ($5 \lesssim x/d \lesssim 20$) of the jet indicated that the interaction between the opposite shear layers is felt on $\overline{v\theta}$ slightly earlier and more strongly than it is felt on $\overline{uv}$. Although results at $x/d = 5$ are retained here, the previous considerations make it clear that self-preservation cannot strictly be expected at this station.

The shape of the mean temperature profiles in Fig. 1 reflects that already reported by Fiedler [3] but differs from that reported by Sunyach [26] or Sunyach and Mathieu [27]. The present measurements, like those of [3], indicate that the rate of change of T/T_j with η is small in the range $-0.04 \lesssim \eta \lesssim 0.08$. In this range, $\overline{uv}/U_j^2$ and $\overline{v\theta}/U_j T_j$ are relatively large and their

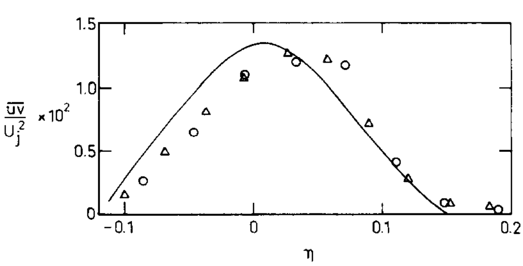

FIG. 2. Reynolds shear stress distributions. Measured: ○, $x/d = 4$; △, $x/d = 5$. Calculated assuming self-preservation: ——.

variation with η is also small. Included in Figs. 2 and 3 are calculations of $\overline{uv}$ and $\overline{v\theta}$, obtained with the mean momentum and mean enthalpy equations, respectively. The calculations are based on the assumption of self-preservation, the measured mean velocity and mean temperature profiles being used as input to the calculations. Agreement between calculated and measured values of $\overline{uv}$ (Fig. 2) can be described as reasonable, the location of the measured maximum being slightly underestimated by the calculation. As noted previously, the discrepancy between the self-preserving calculation (Fig. 3) and measurements at $x/d = 5$ is not unexpected but the calculation underestimates the measured distribution, on the central part of the flow, at $x/d = 4$. For $\eta \gtrsim 0.08$, both sets of measurements are affected by the occurrence of flow reversal. Discrepancies between $\overline{uv}$ measurements obtained in different investigations have already been noted by Batt [28], who suggested that the relatively large spread in published data for $\overline{uv}/U_j^2$ may be partly explained by "the hot wire experimental technique and/or moderate difference in test conditions". Sunyach [26] and Batt [28] found reasonable agreement between calculated and measured values of $\overline{uv}$. Batt found relatively large discrepancies between calculated and measured values of $\overline{v\theta}$; only a calculation of $\overline{v\theta}$ was reported by Sunyach [26]. Fiedler [3] reported a calculation of $\overline{v\theta}$ and measurements of $\overline{v\theta}/U_j T_j$ were reported, at four streamwise stations in presumably the same flow, by Fiedler *et al.* [29]. These measurement closely satisfy self-preservation but their magnitude is smaller, by about 35%, than the calculation reported in [3].

The turbulent Prandtl number Pr_t, derived from measurements of $\overline{uv}$, $\overline{v\theta}$, U and T is presented in Fig. 5. Also shown in this figure are distributions of Pr_t derived from the data of Fiedler [3, 4] and Sunyach [26]. In the former case, measurements of U and T and the distribution of $\overline{v\theta}$ calculated from these measurements were used. It was assumed that the appropriate $\overline{uv}$ distribution was that presented by Wygnanski and Fiedler [5] in an isothermal mixing layer (whilst a trip was used in [5], the initial boundary layer was laminar for [3, 4]). In the latter case, measured distributions of

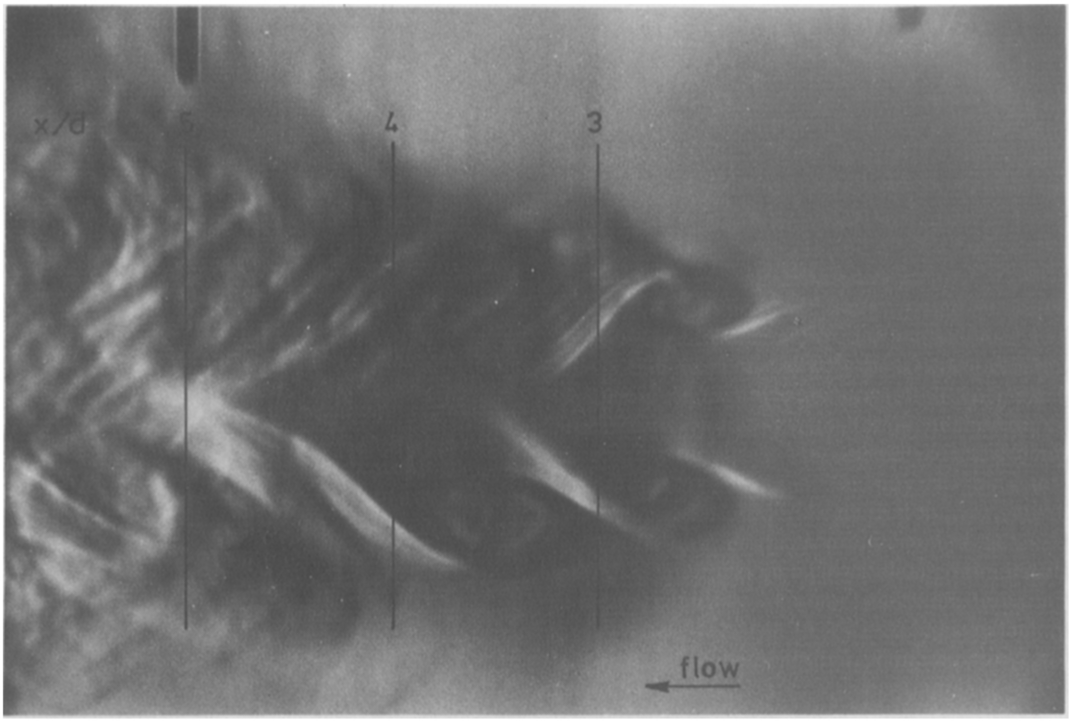

FIG. 4. Schlieren photograph of near field of plane jet, flow is right to left.

Pr_t were determined using Sunyach's measurements of U, T and $\overline{uv}$ and his calculation of $\overline{v\theta}$. While the three data sets in Fig. 5 exhibit differences in the magnitude of Pr_t, they all indicate a region near $\eta = 0$ where Pr_t does not vary appreciably. Perhaps the main feature of this figure is the relatively small value, in this region, of Pr_t. The present values of Pr_t fall between those inferred from the two other investigations. Speculatively, the small magnitude of Pr_t may be associated with the relatively large degree of organisation of the mixing layer. For the mixing layer investigated by Fiedler [3, 4], the initial boundary layer was laminar and the presence of coherent large scale structures was verified either by flow visualisation or with a rake of temperature sensors. For the present mixing layer, the initial boundary layer is also laminar and coherent

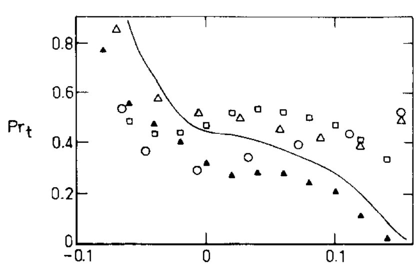

FIG. 5. Turbulent Prandtl number distributions. Present measurements: ○, $x/d = 4$; △, $x/d = 5$; ——, using calculated shear stress and heat flux measurements. ▲, using data of [3, 4]; □, using data of [26, 27].

structures are clearly seen in the schlieren photograph of Fig. 4. The symmetric disposition of the structures with respect to the jet centreline implies a strong coherence between the structures in the opposite mixing layers. When the initial boundary layers were tripped, it was difficult to discern coherence from the schlieren photographs. Chandrsuda *et al.* [11] showed that the essentially two-dimensional coherent structures of Brown and Roshko [7] are formed only if the free stream turbulence is low. Batt [28] presented two distributions of Pr_t. The distribution which was obtained using calculated values of $\overline{uv}$, $\overline{v\theta}$ indicated a value of about 0.5 for Pr_t. Values as large as 0.8 near $\eta = 0$ were obtained when measured values of $\overline{uv}$ and $\overline{v\theta}$ were used. Batt noted, however, that the turbulent motion in his shear layer is "characterised more by random and/or three-dimensionality effects than by large-scale two-dimensional coherent structures". These considerations indicate that the effect of initial conditions on the distribution of Pr_t, but more generally on the mechanisms of momentum and heat transfer, should be investigated further.

Coherent structures have been detected in other turbulent shear flows, such as a boundary layer, a two-dimensional plane jet (e.g. [30]) and a plane wake (e.g. [6]) whereas, in contrast, their existence in a quasi-homogeneous shear flow [31] has not been substantiated. In the fully turbulent part of the boundary layer $Pr_t \simeq 0.9$ while a value of 1.1 was obtained by Tavoularis and Corrsin [31] in their quasi-homogeneous shear flow with constant temperature gradient. These previous considerations support the

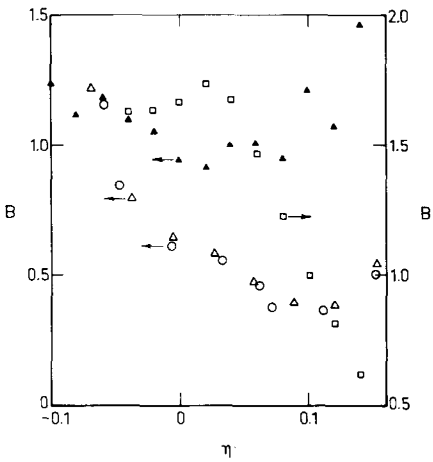

FIG. 6. Distributions of the parameter B, symbols are as in Fig. 5.

speculation that an inverse relationship may exist between the magnitude of Pr_t, and possibly other turbulence parameters, and the degree of coherence of the flow. Measured values of Pr_t in plane jets and wakes are only slightly larger than the previously discussed mixing layer values.

The parameter B, introduced by Fulachier [32] and Fulachier and Dumas [33], is shown in Fig. 6. B does not change significantly over a region for which Pr_t does not vary appreciably. This region is relatively narrow, thus contrasting with the situation in a boundary layer where B is very nearly constant across the whole layer. The difference between the present values of B in Fig. 6 and the value of about 1.5 in a quasi-homogeneous shear flow [31] or in a boundary layer [33] seems consistent with the difference in the values of Pr_t for these different flows.

4. SPECTRA

The part of the mixing layer which corresponds to nearly constant or slowly varying Reynolds stresses, heat fluxes and Pr_t or B distributions is also associated with a relatively strong coherence. An appropriate measure of this coherence is the spectral coherence $Coh_{\alpha\beta}$ between fluctuations α and β. The maximum value $\widehat{Coh}_{\alpha\beta}$ of this coherence is shown in Fig. 7 for two pairs (u, v) and (v, θ) of fluctuations (α, β) at $x/d = 4$. Both $\widehat{Coh}_{uv}$ and $\widehat{Coh}_{v\theta}$ are large over a significant range of η. The frequency at which the maximum coherence occurs is independent of η and corresponds to a Strouhal number, based on x and U_j (note x and U_j are relevant scales for a self-preserving mixing layer and are retained), given by $fx/U_j \simeq 1.1$. Rajagopalan and Antonia [34] noted that the frequency of dominant peaks in temperature spectra in their mixing layer was inversely proportional to x. Their measurements indicated that this frequency corresponds to $fx/U_j \simeq 0.96$. Oster *et al.* [10] investigated the influence of an oscillating trailing edge flap on the structure and development of a two-stream mixing layer for different oscillation frequencies. They found a saturation Strouhal number fx/U_c, based on the convection velocity U_c of the large structures, of about 2.4. The convection velocity U_c was taken equal to the arithmetic mean of the velocities of the two streams. If we assume that for the present flow $U_c = U_j/2$, the present results indicate a value of $fx/U_c \simeq 2.2$ which is in reasonable agreement with the result of Oster *et al.* [10]. It should also be mentioned that at $x/d = 4$, the present value of fx/U_j corresponds to a Strouhal number fd/U_j, based on the nozzle width d, of 0.27. This value is close to the value of 0.3 obtained by Crow and Champagne [35] for the average Strouhal number associated with large scale vortex puffs in the noise-producing region of a circular jet.

Co-spectra for (u, v) and (v, θ), shown in Fig. 8 for $\eta = -0.046$, exhibit differences. The peak in Co_{uv} occurs at a slightly smaller frequency than that in $Co_{v\theta}$. For frequencies extending up to $fx/U_j \simeq 0.88$ ($\ln fx/U_j \simeq -0.13$), Co_{uv} is consistently larger than $Co_{v\theta}$. At larger frequencies, the trend is reversed. The difference between F_u and F_θ in Fig. 9 reflects that between Co_{uv} and $Co_{v\theta}$. The spectral densities of all three velocity fluctuations and of the temperature fluctuation exhibit a pronounced peak at $fx/U_j \simeq 1.1$ ($\ln fx/U_j \simeq 0.095$). For smaller frequencies, F_u and F_w are appreciably larger than F_θ but F_v is remarkably close to F_θ for almost the whole frequency range. The spectrum F_q corresponding to $\overline{q^2}$ is also shown in Fig. 9. Since $\overline{v^2}$

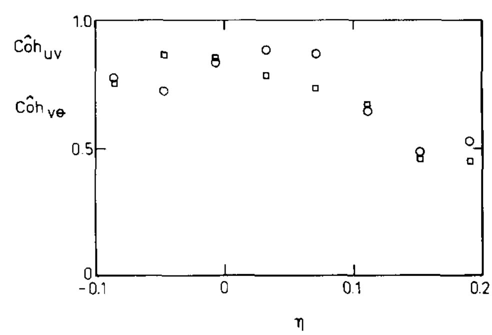

FIG. 7. Maximum coherences between u and v and between v and θ at $x/d = 4$. ○, $\widehat{Coh}_{uv}$; □, $\widehat{Coh}_{v\theta}$.

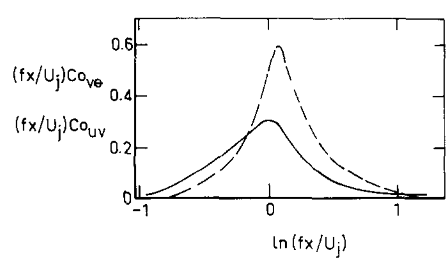

FIG. 8. Co-spectra between u and v and between v and θ at $x/d = 4$ ($\eta = -0.046$). Correlation coefficients between u and v and between v and θ are 0.25 and 0.33, respectively. ——, $fx/U_j\, Co_{uv}$; - - -, $fx/U_j\, Co_{v\theta}$.

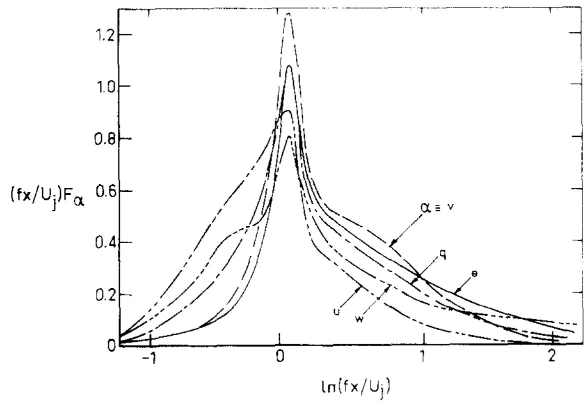

FIG. 9. Spectra corresponding to $\overline{u^2}$, $\overline{v^2}$, $\overline{w^2}$, $\overline{q^2}$ and $\overline{\theta^2}$ at $x/d = 4$ ($\eta = -0.046$). ———, fx/U_jF_q; ——, fx/U_jF_θ; – – – –, fx/U_jF_u; — —, fx/U_jF_v; — - - - —, fx/U_jF_w.

makes a significant contribution to $\overline{q^2}$ at this location in the flow ($\overline{v^2}/\overline{q^2} \simeq 0.58$ at $\eta = -0.046$), F_q is a closer approximation to F_θ than either F_u or F_w. Although F_q is in closer agreement with F_θ at frequencies equal to or greater than the peak frequency, F_v is a better approximation to F_θ than F_q at smaller frequencies. Similar results to those shown in Fig. 9 were obtained at two other values of η ($\simeq 0$ and 0.03).

A close similarity between F_q and F_θ was previously established in [32, 33] for a turbulent boundary layer over a range of frequencies accounting for most of the turbulent energy or temperature variance. More recently [36] this similarity was extended to several other flows. Although this spectral similarity is not unreasonable in the present flow, over a relatively narrow frequency band centered on the average frequency of the coherent structures of the flow, a closer similarity exists between F_v and F_θ over a wider frequency range.

5. CONCLUSIONS

The present mixing layer exhibits, like that investigated by Fiedler [3, 4], a region where the mean temperature does not vary appreciably. In this region, the Reynolds shear stress and the lateral heat flux also vary slowly and their magnitude is large. This region can also be identified with a large spectral coherence, a close similarity between spectra of the lateral velocity fluctuation and of temperature, and a small value, typically about 0.4, of the turbulent Prandtl number Pr_t, inferred either from measurements or from calculations based on self-preserving mean velocity and mean temperature distributions. The dimensionless parameter B is also small, typically about 0.5, in this region. These values of Pr_t and B are significantly smaller than those previously reported in other less coherent shear flows, such as the boundary layer or the quasi-homogeneous shear flow. Speculatively, an inverse relationship may exist between parameters such as Pr_t and B and the coherence of the flow but this speculation and the likely influence of initial and boundary conditions require further investigation.

Acknowledgement—A.J.C. and R.A.A. acknowledge the support of the Australian Research Grants Scheme.

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NOMBRE DE PRANDTL TURBULENT ET CARACTERISTIQUES SPECTRALES D'UNE COUCHE DE MELANGE TURBULENT

Résumé—Des mesures des fluctuations des trois composantes de vitesse et celles de la température sont faites dans une couche de mélange thermique associée à un jet plan turbulent. Dans une région de l'écoulement pour laquelle les contraintes de Reynolds et les flux de chaleur sont importants, le nombre de Prandtl turbulent est égal à 0, 4 environ. La faible valeur du nombre de Prandtl turbulent ici et dans d'autres études de couche de mélange semble refléter la relativement forte cohérence de l'écoulement. Les spectres et les spectres croisés des fluctuations de vitesse et de température montrent un pic prononcé à la fréquence moyenne du mouvement cohérent. Une similitude étroite est notée entre le spectre de vitesse latérale et le spectre de température.

TURBULENTE PRANDTL-ZAHL UND SPEKTRAL-EIGENSCHAFTEN EINER TURBULENTEN MISCHUNGSSCHICHT

Zusammenfassung—Es sind Messungen der dreidimensionalen Geschwindigkeits- und Temperaturschwankungen in der thermischen Mischungsschicht eines ebenen turbulenten Strahls durchgeführt worden. In einem Strömungsgebiet, in welchem die Scherkräfte und Wärmestromdichten groß sind, beträgt die turbulente Prandtl-Zahl ungefähr 0,4. Der niedrige Betrag der turbulenten Prandtl-Zahl in der vorliegenden und in anderen Mischungsschicht-Untersuchungen scheint die relativ starke Kohärenz der Strömung widerzuspiegeln. Leistungsspektren und Kreuzleistungsspektren von Geschwindigkeit und Temperatur zeigen ein ausgesprochenes Maximum bei der Durchschnittsfrequenz der kohärenten Bewegung. Eine starke Ähnlichkeit wird zwischen den Leistungsspektren von Lateralgeschwindigkeit und Temperatur beobachtet.

ТУРБУЛЕНТНОЕ ЧИСЛО ПРАНДТЛЯ И СПЕКТРАЛЬНЫЕ ХАРАКТЕРИСТИКИ ТУРБУЛЕНТНОГО СЛОЯ СМЕШЕНИЯ

Аннотация—Проведены измерения трех составляющих флуктуаций скорости и пульсаций температуры в тепловом слое смешения, формирующемся в турбулентной плоской струе. В области течения, для которой рейнольдсовы напряжения и тепловые потоки велики, турбулентное число Прандтля приблизительно равно 0,4. Оказывается, что малая величина турбулентного числа Прандтля при исследовании данного и других слоев смешения отражает относительно сильную когерентность течения. Энергетические и взаимные спектры пульсаций скорости и температуры имеют ярко выраженные пики при средней частоте когерентного движения. Отмечено близкое подобие между спектром поперечных пульсаций скорости и спектром температуры.