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INSTANTANEOUS VELOCITY AND PRESSURE MEASUREMENTS IN A PLANE TURBULENT MIXING LAYER

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ABSTRACT

This paper describes fast-response pressure probe measurements in the single stream mixing layer and potential core forming the initial region of a plane turbulent jet. Comparison with X-probe measurements of the mean velocities and Reynolds stresses shows that the new technique has reasonable accuracy. Furthermore, the correlation of the pressure and the streamwise velocity behaves correctly as the potential flow is approached. These results demonstrate the probe's ability to measure the pressure-related quantities in the Reynolds stress transport equations such as the correlation of the pressure and the cross-stream velocity. This correlation is compared to the triple velocity products that appear with it in the turbulent diffusion of turbulent kinetic energy.

INTRODUCTION

Much is known about the mean velocity and Reynolds stress distributions in a wide range of turbulent flows but there are important terms in the transport equations for the latter which contain correlations involving the fluctuating pressure. These terms have yet been measured satisfactorily. For example, the turbulent diffusion term in the equation for the turbulent kinetic energy, $k = (\overline{u^2} + \overline{v^2} + \overline{w^2})/2$, where the terms in parentheses are the streamwise, normal, and spanwise normal stress respectively, contains $\overline{pv}$, the correlation between the fluctuating pressure p and the normal velocity v. $\overline{pv}$ is generally held to be negligible, but has not been measured to an accuracy comparable to that of the turbulent triple products, such as $\overline{u^2v}$, which also contribute to the turbulent diffusion.

Similarly, the main source term in the transport equation for $\overline{uv}$, the primary Reynolds shear stress for a two-dimensional flow, involves p and the instantaneous rate of strain. Measurements of this term would be extremely useful for the development of turbulence models.

One way of obtaining at least some of the pressure containing terms is to use a fast-response pressure probe. This paper describes measurements taken with the four-hole probe described by Hooper and Musgrove (1997) in the single stream mixing layer documented by Guo and Wood (1998). The probe measures p, u, v, and w to an upper frequency of about 1.5 kHz. Hooper and Musgrove (1997) reported accurate pressure probe values of the Reynolds stresses in turbulent pipe flow. Here we consider a flow with a much higher turbulence level towards its outer edge, and a potential core that allows a useful check on the accuracy of the pressure-velocity correlations. By comparing pressure and X-probe results in the region where the latter are not compromised by high turbulence, we demonstrate that the pressure probe measures the Reynolds stresses with acceptable accuracy. As a step towards the goal of measuring the pressure-containing terms, we then present distributions of the dynamically important $\overline{pv}$ and the dynamically useless $\overline{pu}$. The latter, however, when repackaged as a correlation coefficient, should approach -1 in the potential flow, and the present results are consistent with this expectation.

EXPERIMENTAL METHOD

The measurements were obtained in the single stream mixing layer described by Guo and Wood (1998). That paper demonstrates the excellent two-dimensionality of the flow and the accuracy of the mean velocity and Reynolds stress measurements obtained using standard X-probe (DANTEC 55P51) hot-wire anemometry at a free-stream velocity, U_0, of 30 m/sec. Briefly, at each measurement point, the probe was sampled in four roll positions to obtain all three mean velocities, all six Reynolds stresses, and all ten triple velocity products. The measurements reported here were obtained at $x/D = 3$ and 5, where x is the streamwise distance measured from the wind tunnel exit and $D = 52$ mm, is the height of the exit flow.

Pressure probe measurements were confined to these larger values of x/D to maximise the spatial resolution. The particular probe used had pressure tappings of 0.5 mm diameter and a roughly spherical measuring volume of radius of about 1.4 mm. This volume is greater than, but comparable to, that of the X-probe. The pressure probe measurement system was as described by Musgrove and Hooper (1997). At present the data processing software determines the mean velocities and Reynolds stresses along with the pressure-velocity correlations. The elementary extension to obtain the triple velocity products has not yet been done.

In the figures containing the results, the normal coordinate y has its origin at the tunnel centreline, so that $y/D = 0.5$ is level with upper lip of the contraction.

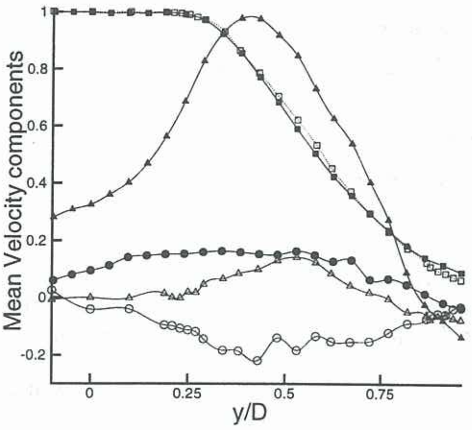

Figure 1 : Mean velocities at $x/D = 3$. U/U_0, □ ; $10V/U_0$, Δ ; $10W/U_0$, ○ . Open symbols show hot-wire data, filled symbols show pressure probe data. Note the increased scale for V and W.

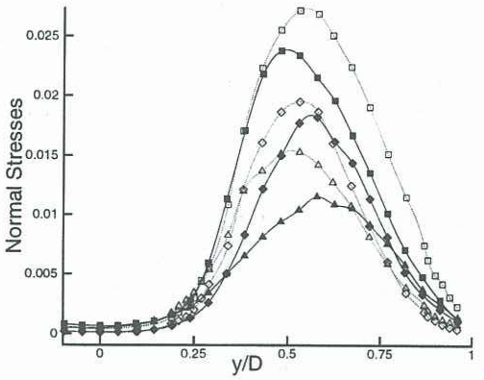

Figure 2 : Normal stresses at $x/D = 3$. $\overline{u^2}/U_0^2$, □ ; $\overline{v^2}/U_0^2$, Δ ; $\overline{w^2}/U_0^2$, ◊. Open symbols show hot-wire data, filled symbols show pressure probe data.

RESULTS and DISCUSSION

The three mean velocities are shown in Figure 1 at $x/D = 3$ and the normal and shear stresses for the same location in Figures 2 and 3 respectively. The agreement in the streamwise velocity, U, is satisfactory even in the high turbulence region, roughly $y/D > 0.5$, where the local turbulence intensity, $\sqrt{\overline{u^2}}/U$, exceeds 25%. The pressure probe accepts any measurement for which the angle between the instantaneous velocity vector and the probe axis (parallel to the x-direction) lies within a cone whose apex angle is 90° and the data reduction program outputs the number of acceptances. This number, as a fraction of the total number of samples, is shown in Figure 4 for $x/D = 3$. X-probes tend to over-estimate U when the turbulence level is high, eg. Tutu and Chevray (1975), which may be the reason for the differences around $y/D = 0.5$. Similar differences were also found at $x/D = 5$, but these results are not shown. As y/D increases, the decreasing level of U renders the X-probe calibration increasingly uncertain, and this compounds the problems of increasing turbulence level and the change in direction of the mean velocity vector due to the entrainment velocity which becomes finite and negative while $U \rightarrow 0$. Using the continuity equation and the measured U, the normal mean velocity, V, can be shown to have a maximum value of nearly $0.010U_0$ in a self-preserving single stream mixing layer. The X-probe results are consistent with this, but the pressure probe over-estimated V (and did so at $x/D = 5$ as well), even taking into account the probable small pitch error (about 1°) that causes V to be non-zero on the tunnel centreline, $y = 0$.

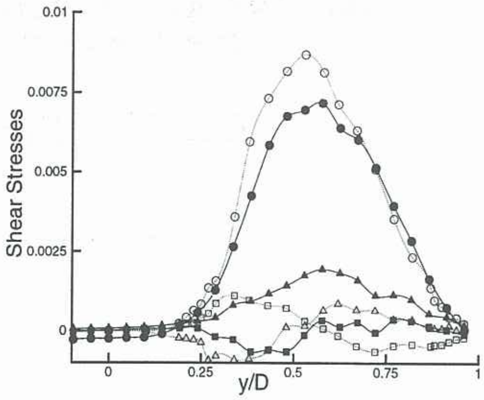

Figure 3 : Reynolds stresses at $x/D = 3$. $\overline{uv}/U_0^2$, ○ ; $\overline{uw}/U_0^2$, □ ; $\overline{vw}/U_0^2$, Δ. Open symbols show hot-wire data, filled symbols show pressure probe data.

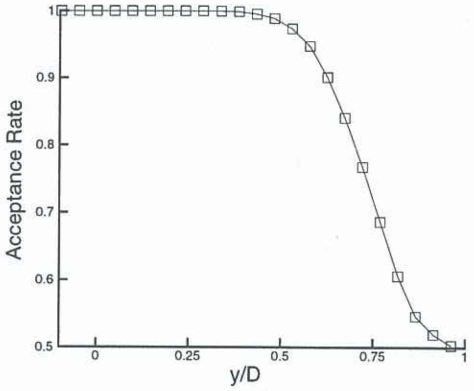

Figure 4 : Acceptance rate of pressure probe data at $x/D = 3$.

Of the turbulence measurements, the agreement between the two methods is best for $\overline{u^2}$ and this occurs in the low turbulence region, $y/D < 0.5$. High intensity should cause an X-probe to under-estimate $\overline{u^2}$, Tutu and Chevray (1975), so the difference between the two techniques for

$y/D > 0.5$, which Figure 5 demonstrates is repeated at $x/D = 5$, is not easily explainable although the reduction in acceptance rate, particularly evident for $y/D > 0.5$, is likely to result in the pressure probe under-estimating the fluctuation levels. On the other hand, the pressure probe should accept most of the velocities in the plane normal to that of the wires of an X-probe. That motion, if significant, will cause an X-probe to *over*-estimate $\overline{u^2}$, eg Clausen and Wood (1989).

The momentum integral equation gives a maximum level of $\overline{uv}$ as $0.010U_0^2$ in a self-preserving single stream mixing layer so the X-probe under-estimates the actual level by around 10%, as suggested by Tutu and Chevray (1975). The pressure probe $\overline{uv}$ is even less accurate at $x/D = 3$, but the agreement between the two methods is substantially better at $x/D = 5$, possibly because of improved spatial resolution. Generally, $\overline{w^2}$ shows better agreement between the two methods than does $\overline{v^2}$, and both display significant discrepancies in the low turbulence region. The remaining shear stresses, $\overline{uw}$ and $\overline{vw}$, should both be zero in a two-dimensional flow, so no definite conclusions about measurement accuracy is possible from the measurements.

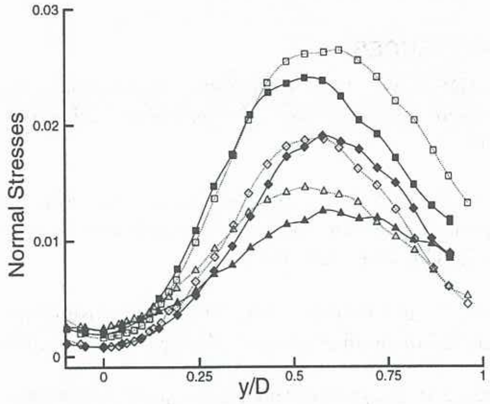

Figure 5 : Normal stresses at $x/D = 5$. Symbols as in Fig. 2.

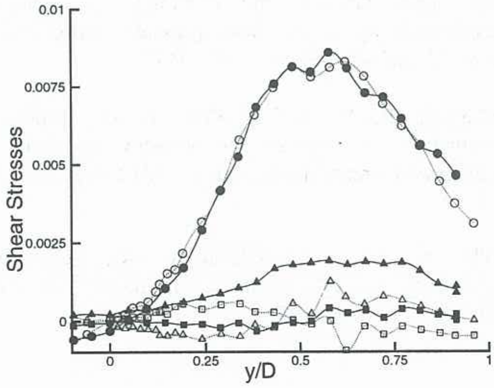

Figure 6: Reynolds stresses at $x/D = 5$. Symbols as in Fig. 3.

The most important of the measured pressure-containing terms is $\overline{pv}$ which appears in the diffusion term for k along with the velocity triple products in the form $(\overline{u^2v} + \overline{w^2v} + \overline{v^3})/2$. The two components of the diffusion are shown in Figure 7 for $x/D = 3$. The pressure term has the same general shape as the triple product term but a lower magnitude, and therefore is not likely to have a significant empirical impact on the budget of k. We are aware of only other measurement of $\overline{pv}$ in a (two-stream) mixing layer, by Spencer and Jones (1971). When normalised to compare with Figure 7, their results are an order of magnitude larger, which caused significant errors in the experimentally determined budget of turbulent kinetic energy.

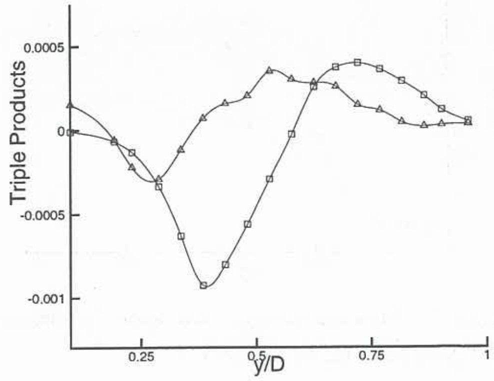

Figure 7 : Turbulent diffusion at $x/D = 3$. $\overline{pv}/\rho U_0^3$, Δ; $(\overline{u^2v} + \overline{w^2v} + \overline{v^3})/2U_0^3$, $\square$.

The correlation between pressure and the streamwise fluctuations, $\overline{pu}$, is shown in Figure 8 in terms of a correlation coefficient R_{pu} defined as

$$R_{pu} = \overline{pu}\Big/\left(\sqrt{\overline{p^2}}\sqrt{\overline{u^2}}\right) \qquad (1)$$

and similarly for R_{pv} and R_{pw} for the coefficients involving the normal and spanwise fluctuations respectively. In the potential flow, the pressure and velocity are related by the unsteady Bernoulli equation which Bradshaw (1967) reduced to

$$-p/\rho \approx (U_0 - U_c)u \qquad (2)$$

provided $U_0 - U_c$, where U_c is the convection velocity of the induced fluctuations, is significantly larger than the level of the fluctuations. Then p and u should be anticorrelated and $R_{pu} \rightarrow -1$ in the potential flow, in agreement with the results of Figure 8. The results at $x/D = 5$ are not shown but it is worth noting that the centreline value of R_{pu} has fallen to -0.7 possibly because of the penetration of turbulence towards the centreline as the mixing layers increase in thickness.

In principle, Equn (2) could be used to find the magnitude of U_c but the results are not encouraging. Using the centreline results from Figure 8 and

$\sqrt{\overline{p^2}}/\rho\sqrt{\overline{u^2}}$ gives $U_c \approx 0.42$, whereas the same data and $\overline{pu}/\rho\,\overline{u^2}$ gives $U_c \approx 0.56$; of course some of the difference comes from R_{pu} not being equal to -1. A value of U_c close to 0.5 is consistent with the measurements outside a two stream mixing layer by Jones et al. (1973) but we are unaware of any measurements that extend as far outside the turbulence as the present ones. The small magnitude of U_c at the centreline - within the turbulence it can reach 0.8, see Jones et al. (1973) - justifies the neglect of the turbulence terms in deriving Equn (2).

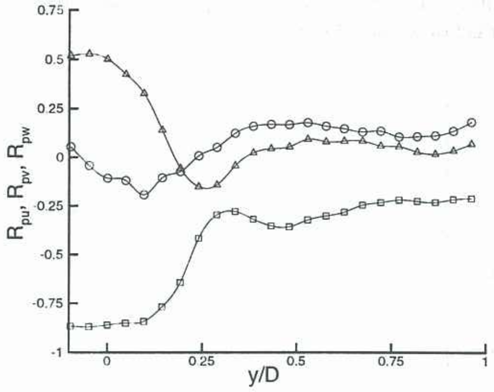

Figure 8 : Pressure-velocity correlation coefficients at $x/D = 3$. R_{pu},□ ; R_{pv},○ ; R_{pw}, Δ .

CONCLUSION

This paper describes the results of a preliminary comparison of the mean velocity and Reynolds stress measurements from a fast response pressure probe with those from standard X-probe hot-wire anemometry. The single stream mixing layer used for the comparison, provides high turbulence levels and a large change in the direction of the mean velocity towards the outer edge. Neither technique is capable of measuring accurately over all the flow, but the general agreement in the streamwise mean velocity was especially encouraging. It appears that the pressure probe over-estimates the normal component of the mean velocity. The Reynolds stress measurements showed best agreement on the high speed side where the turbulence levels are low, but differences exceeding the nominal 10% accuracy for the X-probe, occurred over most of the mixing layer. Since both techniques should under-estimate the turbulence levels, apart from the effect on the X-probe of the transverse motion, it is at present not clear which of the possible mechanisms is responsible for the differences. It is likely that a detailed comparison of the two techniques in a range of flows would be required to resolve the issue.

The agreement between the measurements of the Reynolds stresses improved between $x/D = 3$ and 5 suggests that the pressure probe is more influenced by spatial resolution effects than the X-probe. It is especially interesting that there is better agreement between the measurements of $\overline{uv}$ than between either $\overline{u^2}$ or $\overline{v^2}$.

Two quantities that cannot be measured by hot-wire anemometry were then considered: the correlation between the fluctuating pressure and the axial and normal velocities. The former was shown to agree with the limit imposed by Equn (2) in the potential flow outside the turbulence. The latter, which contributes to the diffusion of turbulent energy, is comparable in magnitude and shape to the other components of the diffusion.

It is our intention to extend these comparative measurements to include the triple products from the pressure probe and to compare the spectra of the velocity fluctuations determined by the two methods.

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