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AN EXPERIMENTAL INVESTIGATION OF A TWO-DIMENSIONAL MIXING LAYER

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SUMMARY The free shear layer formed by the mixing of two parallel streams with different velocities was investigated for large scale turbulent structures. Four different free stream velocity ratios namely 0.87, 0.65, 0.53 and 0.37 were used in this study. Experiments were conducted with (a) thin laminar boundary layers on both sides of the dividing plate at the origin of the mixing layer (b) turbulent boundary layer at the origin. The growth of the mixing layer was nearly linear in all the cases, the rate of growth depending on the velocity ratio. In case (a) the mean velocity profiles exhibited similarity at a distance of about eighty boundary layer thicknesses (δ) from the origin, whereas in case (b) the above condition was reached earlier, at about 20δ. Well defined sinusoidal fluctuations were observed at the beginning stages of mixing for the laminar case and their frequencies scaled with the average boundary layer thickness and the mean of the free stream velocities. Pairing could be observed only during transition from laminar to turbulent condition. Lateral correlation of the longitudinal velocity fluctuations did not indicate two dimensionality of the large eddies except for a short distance. Large scale fluctuations were identified from the hot-wire signals. Their rate of occurrence depended only on the velocity ratio.

1 INTRODUCTION

Turbulent mixing in free shear flows is a fundamental problem in fluid mechanics. In the last two decades a large number of investigations have been carried out yielding significant results. A major contribution to this field was by Brown & Roshko (1974) and Roshko (1976) who showed that the turbulent velocity fluctuations in a mixing layer is not all that random as originally believed but the flow is made up of orderly large structures. They suggested that these structures are primarily responsible for turbulent mixing. This new approach has great bearing not only on the understanding of turbulent free mixing layer but also of immense help for formulating better flow models. Subsequent to their work several investigators Winant & Browand (1974), Browand & Weidmann (1976), Dimotakis & Brown (1976), Pui and Gartshore (1979) have undertaken detailed study of mixing process in free shear layers. However, many questions still remain to be answered, such as the scaling laws of the large scale structures, their exact role in the dynamics of mixing etc.

In the laboratory a mixing layer is produced by the interaction of two streams of different velocities separated by a flow dividing plate. The boundary layers formed on either side of the plate is naturally expected to influence the flow in the early part of the mixing region. If the boundary layers are laminar the mixing layer initially undergoes transition and instability waves are generated before the flow becomes turbulent. On the other hand, if transition occurs in the boundary layer the mixing layer will be turbulent at the origin itself. Since turbulence has considerable memory, the possibility that even at large distances the structure of turbulent flow, being influenced by the boundary layer characteristics cannot be ruled out. The aim of the present investigation is to study the flow characteristics of the mixing layer with laminar as well as turbulent boundary layers on the downstream end of the dividing plate. The results reported here forms a part of the larger research activity undertaken in the Department on the structure of shear flows.

2 EXPERIMENTAL SET-UP

The mixing layer was produced by the interaction of two parallel streams of different velocities, initially separated by a thin dividing plate placed at the center of a converging rectangular duct (fig. 1). The dividing plate was 2.0 mm thick and its trailing edge was sharp and wedge shaped. A low noise centrifugal blower was employed to produce the flow and a large settling chamber containing a honey-comb and a set of fine graded screens, was incorporated upstream of the duct to remove unwanted disturbances from the inlet region. The experiments were conducted for four different velocity ratios U_1/U_2 namely 0.37, 0.53, 0.65 & 0.87 which were obtained by using screens of different

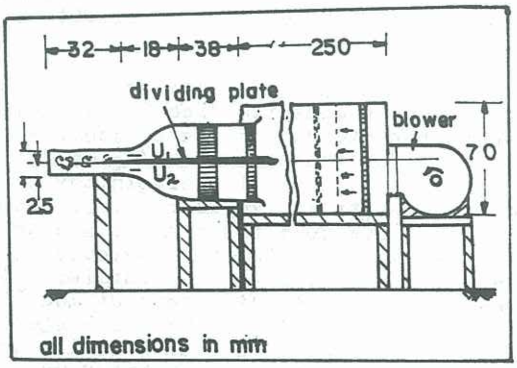


Figure 1 Experimental set-up

porosities in the upper stream ahead of the contraction. In order to maintain the free stream velocities on either side of the mixing layer same as at the exit of the duct, the walls of the duct were extended to a further distance of 30.0 cm downstream of the dividing plate. The velocity U_2 was 1250 cm/sec.

The mean as well as the turbulent velocity fluctuations were measured with a constant temperature hot-wire anemometer system. For lateral correlation at selected frequency bands, a pair of identical Kronhite filters were used as shown in fig. 2.

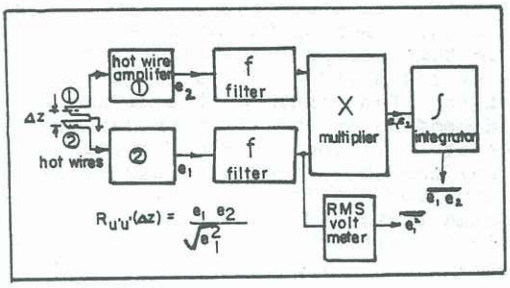


Figure 2 Set-up for correlation measurements at different frequency bands

3 RESULTS AND DISCUSSIONS

The experiments were initially conducted with laminar boundary layers on both sides of the dividing plate. Later they were made turbulent using trips. In the case of the former the thickness of the boundary layer (δ) was the same on either side and equal to 1.0 mm. The tripped boundary layers were nearly 2.0 mm thick on both sides of the plate. The free stream turbulence was negligibly small. Hereafter in this report the laminar case will be referred as Expt. (a) and the other as Expt. (b). Expt.(a) was carried out for all the four velocity ratios whereas Expt. (b) was restricted to only to velocity ratio of 0.37.

The mean as well as the turbulent fluctuating velocities were measured from 0.5 cm downstream of the dividing plate to about 20 cm. The results for the case of U_1/U_2 of 0.37 are shown in fig. 3. Near the origin the profile shapes varied appreciably for Expt. (a) however they settle down to a fixed shape around X = 30 cm. In Expt. (b) the mean velocity profiles exhibited similarity much earlier. The turbulent velocity fluctuations $\tilde{u'}$ and $\tilde{v'}$ required a longer duration to reach equilibrium condition than the mean velocity profiles. Similar trend was exhibited by $\overline{u'v'}$.

The rate of spread of the mixing layer was estimated in the form of the shear layer spread rate parameter (σ), Pui & Gartshore (1979) and the results are in reasonable agreement with those of others (fig. 4). In the above calculations the values of the virtual origins(X_0) were 3.6, 7.5 and 8 cm for U_1/U_2 of 0.37, 0.53 and 0.65 respectively in Expt. (a) and 3.7 cm for U_1/U_2 of 0.37 in Expt. (b). The growth of the mixing layer based on its thickness (0.95 of U_1 and U_2) was linear to Expt. (b) all the way beginning from X = 0 cm whereas in Expt. (a) linearity was observed only beyond X = 6 cm. The angle of spread of the mixing layer based on actual thickness ($\delta_{.95}$ U_1 & U_2) in the linear region showed an increase for lower values of U_1/U_2. For U_1/U_2 of 0.37 the angles of spread were 7.670° and 6.07° in Expt. (a) and Expt. (b) respectively, whereas it was only 2.1° for U_1/U_2 of 0.65 in Expt. (a).

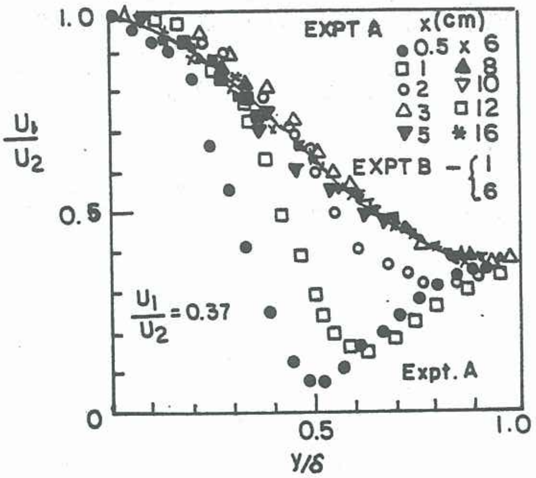
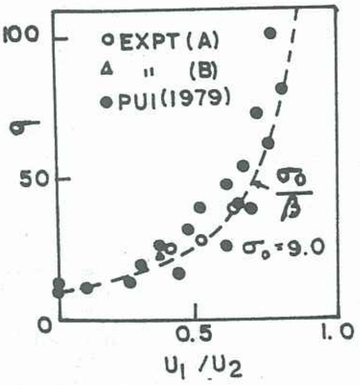


Figure 3 Mean velocity profiles across the mixing layer.



$$\sigma = \left[\sqrt{\pi}/1-\frac{U_1}{U_2}\right]\left[\frac{d(\frac{U_1}{U_2})}{d(y/x-x_0)}\right]$$

$$\beta = \frac{U_2-U_1}{U_1-U_2}$$

Figure 4 Shear layer spread rate parameter

Hot-wire traces exhibited near-sinusoidal fluctuations just downstream of the dividing plate in the case of Expt. (a) indicating the instability modes in the transition region. Their frequencies (n) scaled with $(U_1+U_2)/2(=\overline{U})$ and the boundary layer thickness (δ). The values of $\delta n/\overline{U}$ was 0.3 ± 0.05 in all the experiments. The fluctuations could be observed distinctly upto X = 1 cm. Downstream of this region they exhibited amplitude modulation before becoming turbulent with their frequency remaining the same. No such periodic signals could be seen in Expt. (b). Pairing was observed only in Expt. (a). During this process the initial frequency observed at X = 0 got reduced to half the value before the flow became turbulent (fig. 5). In Expt. (b) the pairing process was absent.

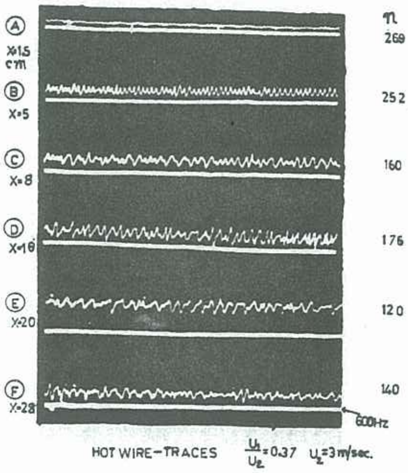


Figure 5 Hot-wire traces to illustrate pairing during transition

The hot-wire signals of the u' fluctuations were used to identify the large scale motions in the mixing layer. For this purpose the output from the hot-wire anemometer was passed through a 20 Hz to 2000 Hz band pass filter. This enhanced the clarity of the large fluctuations so that they could be visually counted. Some typical traces of the filtered signals are shown in Fig. 6, with the large fluctuations marked on them. The

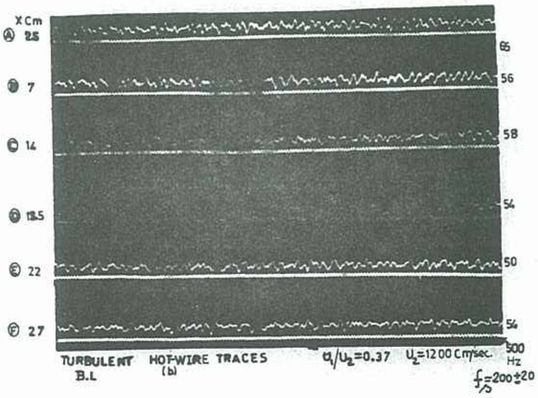


Figure 6 Hot-wire traces of the large fluctuations

number of fluctuations per second (f_s) remained constant all along X for a given flow and the value of f_s depended on U_1/U_2. As U_1/U_2 approached unity f_s decreased and close to unity the amplitude of the fluctuations became extremely small. These large fluctuations were observable even in Expt. (b). For U_1/U_2 of 0.37, f_s was the same and equal to 200 in both Expts. (a) and (b).

It is conjectured that these large fluctuations are the signatures of the coherent large scale turbulent structures. The signal processing technique used here is somewhat similar to that employed to identify the vortices shed behind a circular cylinder as well as the large scale structures in turbulent boundary layers (Badri Narayanan et al. (1977) and Ramaprian & Sivaprasad (1982). Since f_s is constant along X for a given flow, it can be assumed that the large eddy-like structures which are generated at the origin are just convected downstream. As they move along the flow they grow in size resulting in the spreading of the mixing layer. The results of the present experiments were analysed for possible scaling laws for f_s. While (U_2-U_1) seems to be the appropriate velocity scale no suitable length scale could be identified (fig. 7).

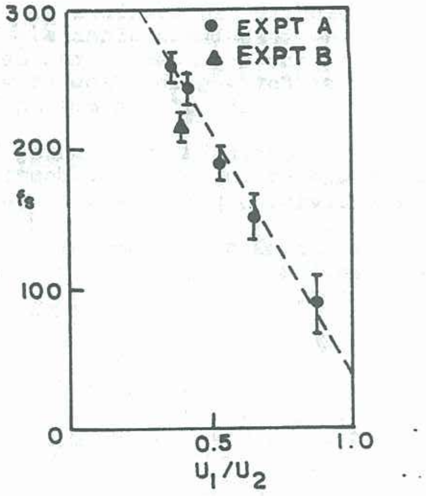


Figure 7 Variation of f_s with velocity ratio

The spatial correlation $R_{uu'}(Z)$ was measured at X = 10 cm in Expt. (a) for U_1/U_2 = 0.37. These experiments were carried out with different upper cut off frequencies to investigate the coherence of the turbulence structure. The results show even for low frequency signals the correlation exists only upto a lateral distance of 1.0 cm (fig. 8).

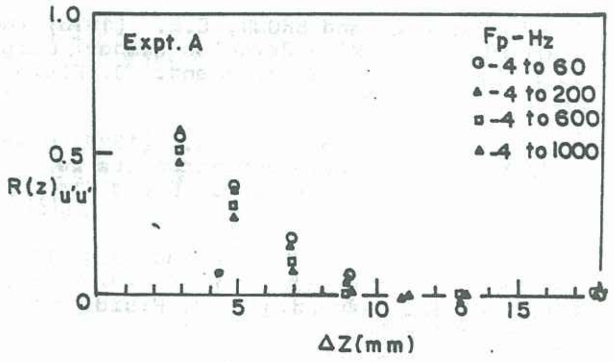


Figure 8 Transverse correlation of u' signals at different frequency bands

Hot-wire signals observed in an oscilloscope also confirmed the above trend. This observation is consistent with those of Chandrasuda and Bradshaw (1976).

4 CONCLUSIONS

Experiments were conducted to investigate the large scale fluctuations in a free mixing layer with laminar as well as turbulent boundary layers on both sides of the dividing plate. The major conclusions are,

(i) the mean velocity profiles in the mixing layer reached similarity earlier than the turbulent velocity fluctuations,

(ii) the growth of the free shear layer was linear except very close to the origin,

(iii) the rate of growth was high for lower velocity ratios,

(iv) large velocity fluctuations were identified from the turbulence signals. Their rate of occurrence depended on the velocity ratios; however for a given flow it was constant along the length of the mixing layer,

(v) pairing was observed only during transition and it was absent when the boundary layers on the dividing plate were turbulent,

(vi) lateral correlation measurements indicated poor spanwise coherence of the large scale fluctuations.

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