Center for Turbulence Research
Annual Research Briefs – 1989

An experimental study of scalar mixing in curved shear layers

By P. S. Karasso AND M. G. Mungal

This report describes the work being undertaken to study the scalar mixing in curved shear layers. First, the motivation for this work and its objectives are described. Second, a description of the experimental rig that has been built is given. Third, some preliminary results (flow visualizations) are discussed, and finally, future steps that will be taken to complete the study are outlined.

1. Introduction

Straight mixing layers have been the object of considerable study over the last twenty years. Curved mixing layers have seen less investigation. Here, we will provide a brief description of the aspects that are important to this work. The characterization of a curved shear layer depends upon the sense of the curvature: if the high speed stream is on the inside of the curvature, it is referred to as the unstable case; the reverse is referred to as the stable case (Fig. 1). For such shear layers, with equal density fluids, two kinds of instability modes are encountered. First, the Kelvin-Helmholtz (K-H) instability which is due to the shear per se and manifests itself with spanwise vortical structures. Second, the Taylor-Görtler (T-G) instability, associated with the centripetal forces due to the streamlines' curvature, which creates streamwise vortical structures. The Taylor-Görtler instability is enhanced in the unstable case and suppressed in the stable one. Plesniak & Johnston (1989) have provided detailed measurements of the turbulence properties of curved mixing layers.

Wang (1984) studied a curved shear layer to determine the flow structure for the stable and the unstable case. He used spatially averaged shadowgraph pictures which can easily mask the real physics of the flow. He found evidence of organized motion for the stable case but more 3-dimensionality and loss of the large-scale (K-H) motion for the unstable case.

Koochesfahani (1984) made concentration field measurements in a plane shear (mixing) layer, where the K-H instability is dominant, producing a non-marching probability density function (pdf) of mixture fraction; a similar result was obtained earlier by Konrad (1976). A new, more plausible model for mixing by Broadwell & Breidenthal (1982) based on the large-scale structures was thus supported.

The existence of streamwise vortical structures in a lower Reynolds number plane shear layer was investigated by Bernal (1981). Image reconstruction by

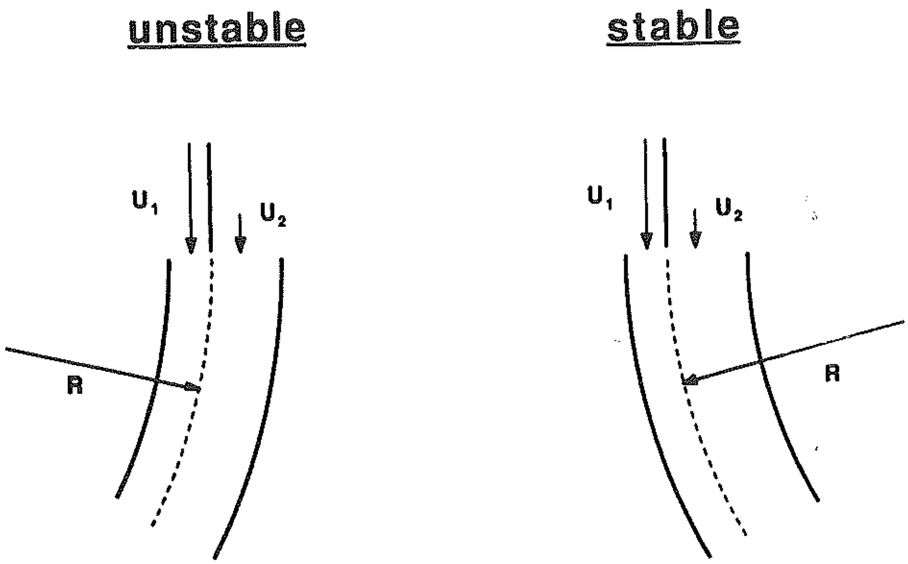

FIGURE 1. Definition of stable vs. unstable curvature

Jimenez, Cogollos and Bernal (1985) revealed the flow structure and suggested possible growth mechanisms.

It is the purpose of this study to understand the flow physics, the molecular mixing and growth rate in curved shear layers at high Reynolds numbers past the mixing transition (up to 80,000 based on velocity difference and visual thickness). The curvature offers a way to "dissociate" the effect of the two instability modes: in the unstable case both K-H and T-G are present and strong whereas in the stable the K-H is strong and the T-G is weak. A detailed quantitative description of the composition field in the fully developed region is sought via pdf measurements. The flow physics is investigated via detailed image reconstruction approaches.

Instantaneous, spatially resolved pictures of high Reynolds numbers curved shear layers do not exist in the literature, so we have chosen to begin there in order to address the question of organized motion. Volume rendering in the $y-z-t$ space has proven to be a most powerful tool to investigate the evolution of structures in flows (Cruyningen, Lozano, Mungal, Hanson, 1989) and will be attempted in the curved layer. It is again noted that Schlieren pictures or shadowgraphs are incompatible with the above ideas and that only instantaneous planar cuts of the layer can reveal the real mechanisms of mixing.

2. Experimental facility & technique

A schematic of the facility that was built for this study is shown in Fig 2. It is a blow-down water tunnel made entirely out of plexiglass which allows full

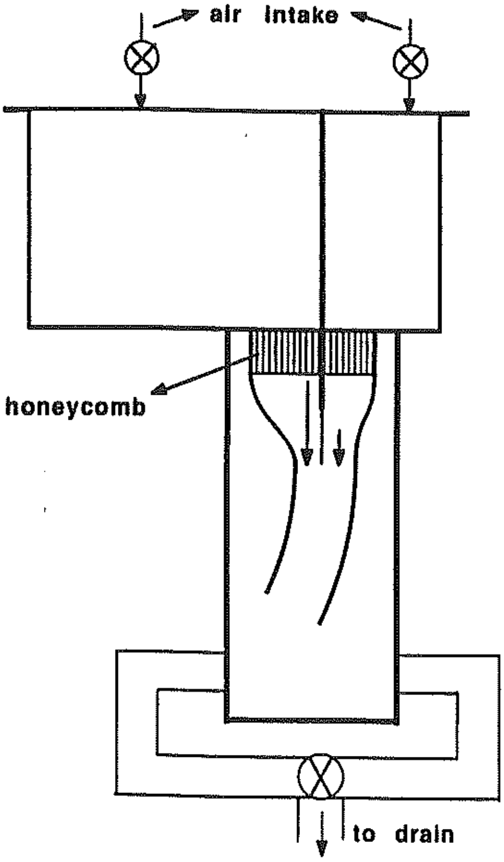

FIGURE 2. Layout of Rig

optical access. The overhead tank is partitioned so that one side (usually the low-speed) can be totally dyed. The velocity ratio of the two streams and the flow rates can be controlled by means of a draining valve and air-admittance valves. The facility is operated at a velocity ratio of 4:1. A speed of 2 m/s can be achieved on the high speed side, which gives a Reynolds number of about 80,000 towards the end of the test section. The test section size is 16 cm (span) x 10 cm (height) x 30 cm (length). The facility has been mounted over a recently refurbished floor and underground sump tank.

The test section (curved walls, shown in the unstable configuration in Fig. 2) was modelled after Wang's facility and it is considered to be of mild curvature. The run-time of the tunnel ranges from 15 to 30 seconds, depending on the velocity magnitudes.

Flow visualizations are effected with planar laser induced fluorescence (PLIF). A fluorescent dye (sodium fluorescein) is diluted in the low-speed side and the layer is excited with a laser sheet from a 2-Watt Argon-ion laser. The sheet can be directed in the $x-y$ plane (side view), the $x-z$ plane (plan view), and the $y-z$ plane (end view) to give the whole flow field. Fast photography (exposure time 1/1000 sec) with 3200 ASA film was then used, minimizing smearing of the flow field.

3. Present results

Some high Reynolds number flow visualizations are shown below, using the techniques described earlier. The high and low speed streams are at 2 and 0.5 m/s respectively.

Figure 3 shows side views for the stable and the unstable case (flow is from left to right). The K-H rolls are very well defined throughout the whole test section for both cases. The two fiducial marks on each picture are at 15 and 25 cm downstream from the splitter plate (corresponding to Reynolds numbers of approximately 35,000 and 60,000). The large-scale organized motion of the flow prevails into the fully developed region of the shear layer. This photo immediately shows the advantage over spatially integrated measures such as shadowgraphy when compared to Wang's results. The growth of the structures was in general found to be larger for the unstable case. To clarify the overall growth rates, time-averaged pictures are shown in Fig.4 (flow here is from top to bottom). The dots are put there to help the reader follow the mixing layer. It can be seen that the layer grows about 50% more for the unstable case than for the stable one.

In order to investigate the 2-D aspect of the K-H vortices, plan views of both cases are presented. Bands of mixed and unmixed fluid are observed (Fig. 5). Bands were found to be much more defined in the stable case, whereas much more streakiness was evidenced in the unstable case. We believe that this is due to the enhanced T-G instability which creates streamwise structures. Another rather striking event is the fact that the spanwise rolls are seen to occur tilted with respect to the flow direction. This, to our knowledge, has never been reported before and would again show the difficulties in shadow techniques. Various runs were performed to further investigate this fact for a case of a plane 2-D layer at the same high Reynolds number (straight walls can also be easily mounted in the experimental rig). The skewness of the structures was again evidenced.

End views of the layers are not presented here. The reason has to do with the fact that single pictures of this view cannot easily reveal any structures. This view, however, will be heavily emphasized during our upcoming image reconstruction which is addressed in the next section.

We have emphasized here the importance of instantaneous cuts, especially for such high speed flows, in order to understand the real physics underlying the evolution of the structures. Also it is crucial to see that all three views are needed and are complementary to each other. For instance, a side view capturing a tilted object may look very ambiguous, whereas a plan view might reveal it.

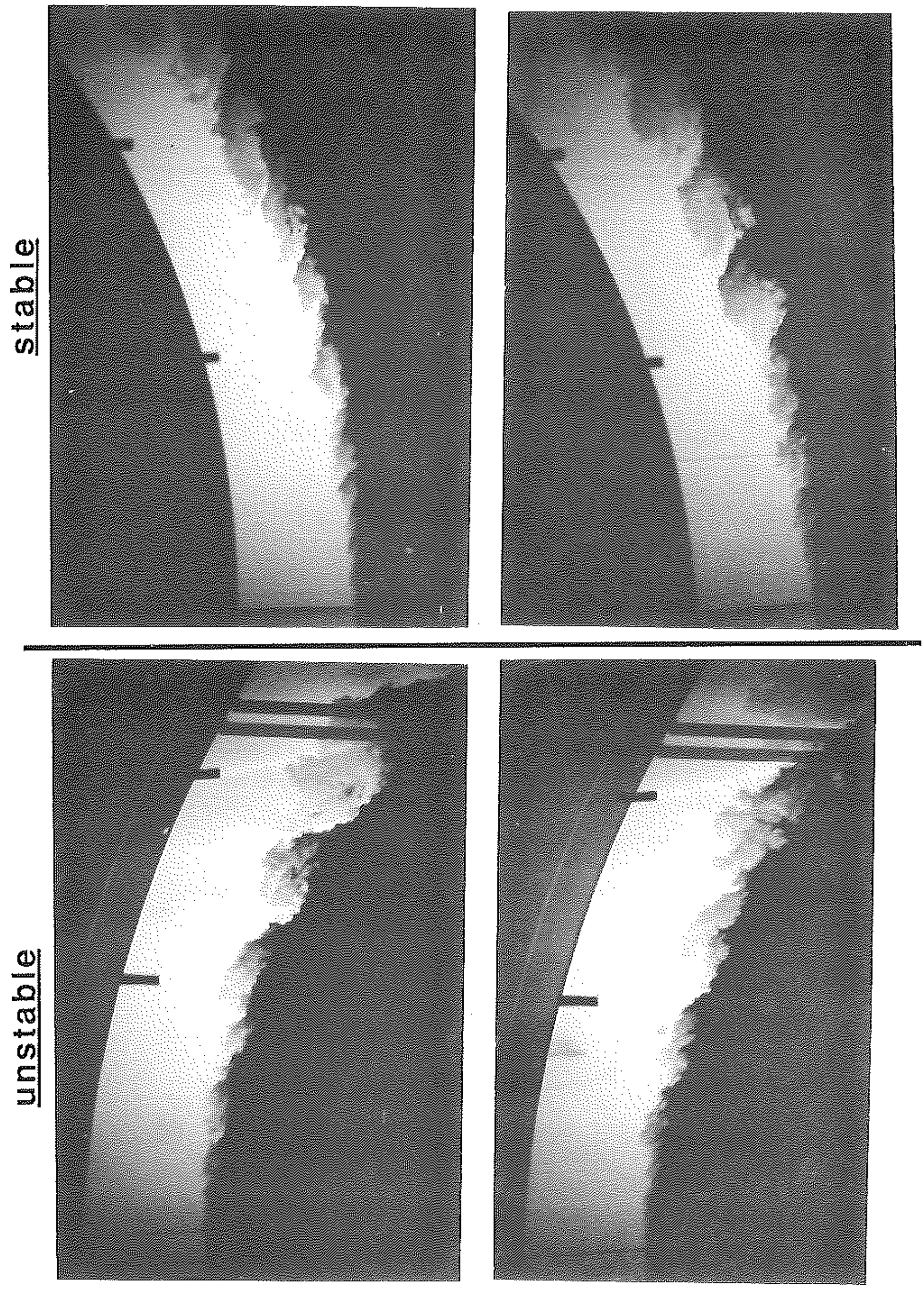

FIGURE 3. Side views of mixing layer, using PLIF. Time exp. 1/1000 sec.

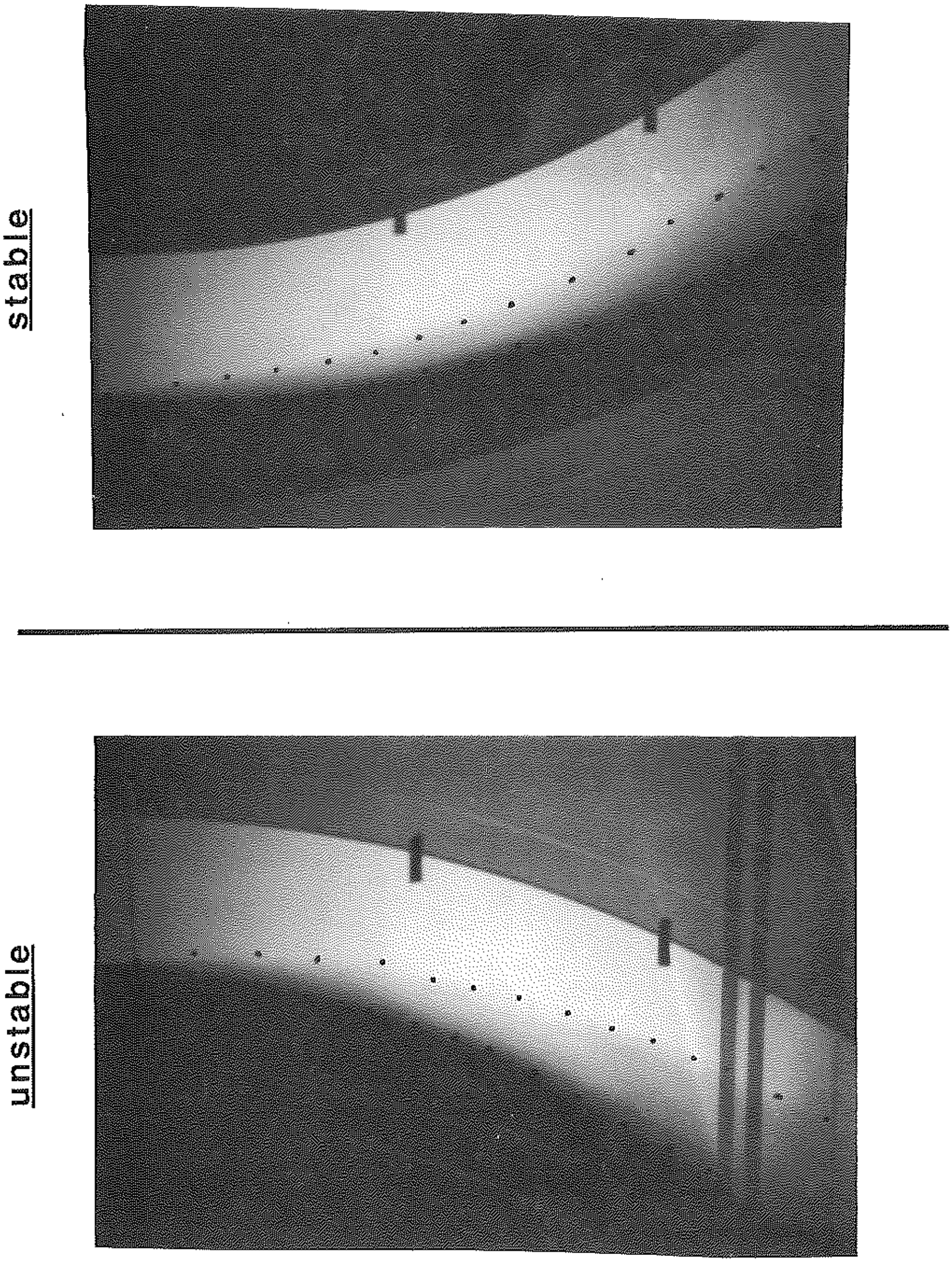

FIGURE 4. Time averaged side views of mixing layer, using PLIF. Time exp. 0.5 sec.

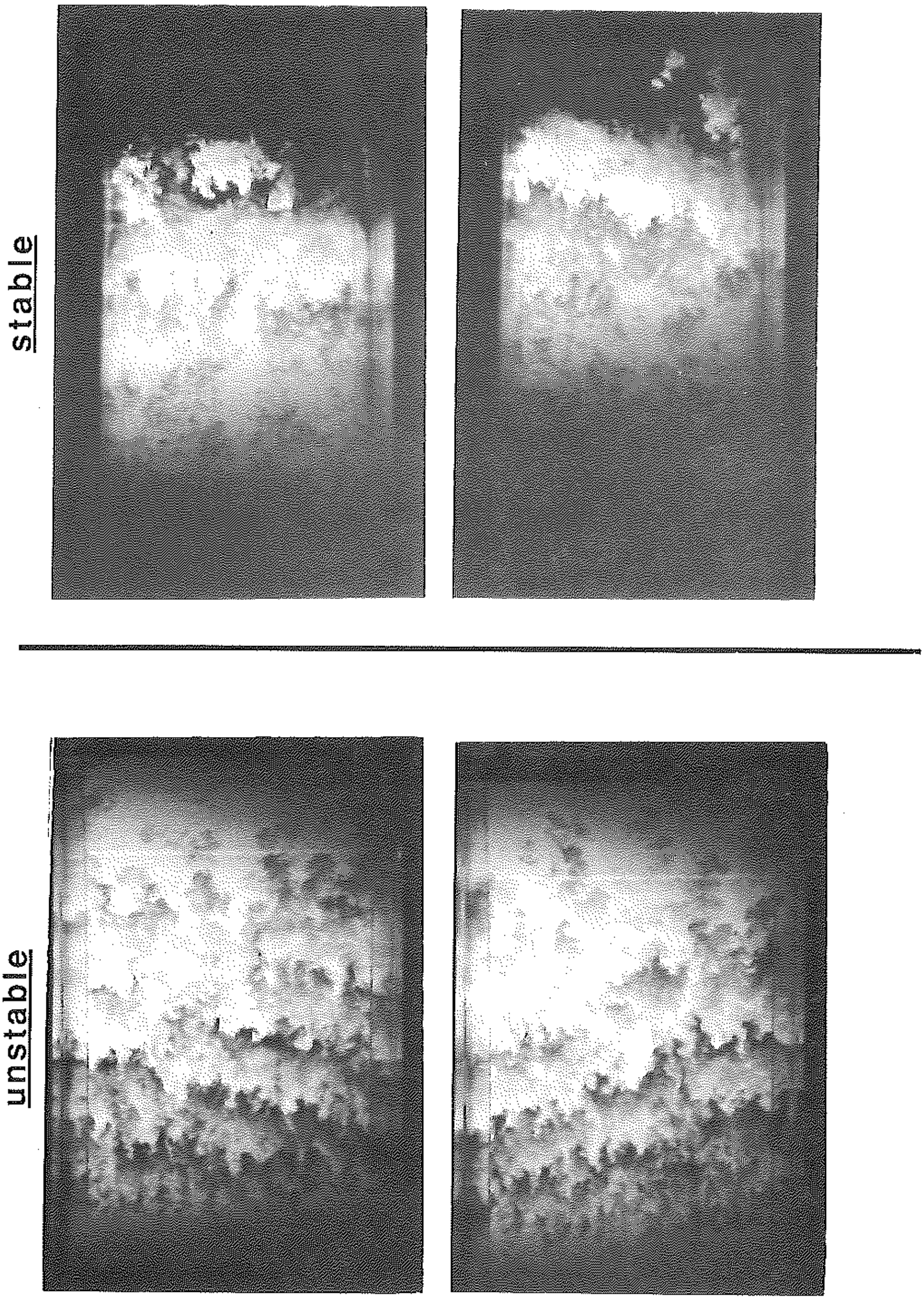

FIGURE 5. Plan views of mixing layer, using PLIF. Time exp. 1/1000 sec.

Similarly a plan view of K-H structures captured while pairing would not show any organization of motion.

4. Future work

The future work has two main objectives: i) Perform image reconstruction of the layer for both curved cases and for a straight case in order to compare the changes in the flow structures and ii) Perform detailed quantitative measurements of the concentration field.

The end view of the mixing layers will be used to get a $y - z - t$ space reconstruction of the flow field. This will be done by using the Pixar computer available at the High Temperature Gasdynamics Laboratory at Stanford University. Sequential digitized images will come from video recording of the flow. It is important that each frame consist of a truly instantaneous cut; therefore, a pulsed 20-Watt Copper-vapor laser will be used. The framing rate must also be sufficient to have sufficient cut planes through a structure. To this end, video framing rates will first be used, followed possibly by the higher framing rate of a Spin Physics recording system, should it be necessary. First reconstructions should occur in the Spring.

The final task is generating the concentration field pdf. For this, the imaging system will consist of a self-scanning linear array camera. The laser source will either be the Copper-vapor laser or the Argon-ion laser. The frame grabber in this case is not a trivial issue because of the extremely high framing rates needed to resolve the flow and the amount of data generated. At this point the hardware problem seems to be resolved and the various components' interfacing problems are being tackled. Once components are bought (computer, A/D board and optics), first results will occur within 3 to 6 months.

5. Summary

Instantaneous planar visualizations of high Reynolds number curved mixing layers were presented. These cuts revealed that the K-H structures are existent and well defined in the fully developed region. Additional views suggest that these structures may occur tilted with respect to the flow. More streakiness in the unstable case suggests a strong T-G instability. The growth rate was found to be about 50% larger for the unstable case. Image reconstruction of the flow field and detailed concentration measurements of the layer will constitute the bulk of our future work.

REFERENCES

BERNAL, L. P. 1981 The Coherent Structure of Turbulent Mixing Layers: I. Similarity of the Primary Vortex Structure. II. Secondary Streamwise Vortex Structure. Ph.D. Thesis, Caltech.

BROADWELL, J. E., & BREIDENTHAL, R. E. 1982 A Simple Model of Mixing and Chemical Reaction in a Turbulent Shear Layer. *J. Fluid Mech.* **125**, 397-410.

DIMOTAKIS, P. E., & BROWN, G. L. 1976 The Mixing Layer at High Reynolds Numbers: Large Structure Dynamics and Entrainment. *J. Fluid Mech.* **78**, 535-560.

JIMENEZ, J., COGOLLOS, M., & BERNAL, P. L. 1985 A Perspective view of the Plane Mixing Layer. *J. Fluid Mech.* **152**, 125-143.

KONRAD, J. H. 1976 An experimental investigation of mixing in two-dimensional turbulent shear flows with application to diffusion limited chemical reactions. Ph.D. Thesis, Caltech.

KOOCHESFAHANI, M. M. 1984 Experiments on Turbulent Mixing and Chemical Reaction in a Liquid Mixing Layer., Ph.D. Thesis, Caltech

PLESNIAK, M. W. & JOHNSTON, J. P. 1989 Reynolds stress evolution in curved two-stream turbulent mixing layers, Seventh Symp. on Turbulent Shear Flows, Stanford, August 1989.

VAN CRUYNINGEN, I., LOZANO, A., MUNGAL, M. G., & HANSON, R. K. 1989 3D Visualization of Temporal Flow Sequences, submitted to AIAA Journal.

WANG, C. 1984 The Effects of Curvature on Turbulent Mixing Layers, Ph.D. Thesis, Caltech.