An experimental study of curved mixing layers: flow visualization using volume rendering

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1. Motivation and objectives

The existence and importance of large-scale spanwise vortical structures for 2-D straight mixing layers has been well documented in the last decade (Brown & Roshko, 1974; Dimotakis & Brown, 1976; Mungal *et al.*, 1985; Konrad 1976; Winant & Browand, 1974). Computer models and simulations have sought to reproduce these vortical structures associated with the Kelvin-Helmholtz (K-H) instability mode which is due to the shear per se (Sandham & Reynolds, 1989). Secondary streamwise vortical structures for the same flows were also seen experimentally (Konrad, 1976; Breidenthal, 1981; Bernal & Roshko, 1986; Lasheras & Choi, 1988); Huang & Ho, 1989) and have recently been given importance in computational efforts. Jimenez *et al.* (1985) first performed a reconstruction of the plane mixing layer for Reynolds numbers of about 2,000 and 7,500 (based on the velocity difference and the visual thickness). They found that a system of streamwise vortices exists on top of the spanwise vortices. The streamwise vortical structures were very well defined for the $R_e \sim 2,000$ case but less so for the $R_e \sim 7,500$ case.

Curved mixing layers can be characterized as stable (the high-speed stream is placed on the outside of the longitudinal bend), leading to a suppression of the Taylor-Görtler (T-G) instability, and unstable (high-speed stream on the inside of the bend), leading to an enhancement of the T-G instability (Figure 1). The T-G instability is associated with the centripetal acceleration that the curvature imparts (Wang, 1984; Taylor, 1923). Thus, curvature superimposed on 2-D shear layer flows provides a way for studying the importance of streamwise vorticity, its competition with spanwise vorticity, and changes to entrainment and mixing. Furthermore, the outcome of the competition of a relatively enhanced or suppressed T-G instability with the K-H instability offers the possibility of achieving passive mixing enhancement.

Konrad (1976) and Koochesfahani & Dimotakis (1986), performed measurements of the probability density function (pdf) of the mixture fraction in a plane mixing layer and found it to be invariant with lateral distance across the layer for a Reynolds number not greater than 23,000. This result is consistent with the characterization of the K-H instability as the dominant one in the plane mixing layer. In the case of curved mixing layers, similar pdf measurements are our long term goal, with differences in the shape of these pdf's reflecting differences in the entrainment and mixing of this flow field. The Reynolds number dependence of the structure of the mixing layers will also be explored. As a first step in understanding the competition between the K-H and the T-G instabilities and the resulting changes to the structure of the flow, we attempt here to provide highly resolved visualizations of the flow structure for the stable and the unstable configurations. The straight layer is also visualized for comparison with earlier works.

2. Accomplishments

2.1. Experimental facility and conditions

The experimental facility consists of a blow-down water tunnel which is described in Karasso *et al* (1989). A passive scalar, sodium fluorescein, is diluted uniformly in the low-speed fluid. An Argon-ion laser is used to generate a laser sheet at the $y-z$ plane, normal to the flow direction (Figure 2). Two positions are examined, at $x = 4.8$ cm and $x = 9.5$ cm downstream from the splitter plate, yielding Reynolds numbers of about 6,500 and 12,000 respectively, based on the velocity difference and the visual thickness. These Reynolds numbers correspond to the pre-transition and to the transition field of the straight layer. Laser induced fluorescence movies are acquired using a motion picture camera operated at 400 frames/sec with an exposure time of 1/1000 sec. The experiments are performed for both the stable and the unstable configuration as well as for the straight shear layer configuration.

Photos showing planar cuts, taken with 3200 ASA photographic film, were presented in Karasso *et al* (1989). The photos showed that the mixing layer grows about 50% more for the unstable than for the stable case. Hence, the unstable case can be immediately characterized by growth enhancement. Detailed changes to the pdf of the mixture fracture are not known at present, so it is unclear if the growth changes correspond to mixing changes.

Single, unrelated instantaneous cuts such as the ones shown in Karasso *et al* (1989), although useful, have an inherent difficulty in presenting the time evolution of the flow and more importantly in simultaneously displaying the streamwise vortical structures of the flow field. To circumvent this difficulty, we use the technique of volume rendering, which is described next.

2.2. Volume rendering results

The essential idea of volume rendering (Van Cruyningen *et al*, 1991; Drebin *et al*, 1988) consists of stacking sequential frames to produce a three-dimensional data-object. Here, $y-z$ views of the layer (the high framing rate movies), once digitized, are stacked sequentially as a function of time t on a Pixar image computer. This three-dimensional data volume is used to extract surfaces that retain the resolution of the digitized frames. Viewing the rendered surfaces is made possible by shading with a white light source, the position of which is preselected. Rotating the rendered surfaces with respect to the light source provides different views corresponding to the rotation of a 3-D object in $y-z-t$ space. The results for all cases appear in Figures 3 and 4, where the temporally growing layers are shown from an angle that best displays the streamwise and the spanwise vortical structures. The coordinate system $y-z-t$ is shown at the top left corner of each of the figures. About 60 frames compose each view, corresponding to a real time interval of 0.15 sec, which is converted to length by assuming the average velocity of the two streams of the shear layer.

The renderings show that the two instability modes occur together in a non-destructive way. In the pre-transition field, Figure 3 ($R_e \sim 6,500$), the T-G instability induces streamwise vortices (lines that run from top to bottom on each photograph) which are well defined for all three cases. The width (z) of the field of view shown in the renderings is about 13 cm. The spacing of the streamwise vortical structures is seen to be $\lambda \sim 0.9$ cm for all cases. The K-H instability is also evident at this station. The T-G vortices are seen to ride both on the cores and the braids of the K-H vortices, consistent with the model presented by Bernal & Roshko (1986). The passage frequency of the K-H rolls corresponds to a streamwise length δ of about 1 cm; a ratio of $\lambda/\delta \sim 0.9$ then characterizes all cases at this station. Notice how the present results, for the straight case, show well defined streamwise vortical structures compared to the case of $R_e \sim 7,500$ of Jimenez *et al.* (1985). This difference, we believe, is due to the fact that the present rendering calculations are done by retaining the pixel resolution of the frames that are originally used for stacking, resulting in fewer overall approximations.

In the transition region, Figure 4 ($R_e \sim 12,000$), small scales begin to develop as seen in the irregularities of the rendered surfaces. In the stable case, the K-H instability appears to dominate the T-G instability, while in the unstable case the T-G rolls remain very well defined. The spacing λ for the stable and the unstable cases is seen to be about 1 cm, showing a small increase from the previous station. The straight case shows results that are intermediate to the stable and unstable case. The streamwise to spanwise structure spacing ratio is now $\lambda/\delta \sim 0.5$ due to a decrease in the passage frequency of the K-H rolls.

Although no quantitative measurements for the mixture fraction can be extracted from the present photos, it is clear that the large-scale structures that are seen to persist must be associated with entrainment patterns in shear layer flows and are of ultimate importance in gaining an understanding of the physics of the flow, the resulting mixing, and in modeling. The volume rendering technique presented here seems to be a convenient way to simultaneously demonstrate the occurrence of both K-H and T-G instabilities.

2.3. Summary

In this work, the curved mixing layer is used to provide a means to study the competition of the T-G and the K-H instabilities in a systematic way. At pre-transition Reynolds numbers, both instabilities are evident as seen in the volume renderings. Transition Reynolds numbers are marked by the addition of smaller scales. For the stable and the straight case, the K-H instability appears dominant, while for the unstable case the T-G instability is enhanced.

3. Future plans

The philosophy underlying future work is to generate highly resolved data that characterize the dynamics of mixing in shear layers by varying different parameters of the flow such as: (i) The Reynolds number: The facility allows a change of velocity magnitudes and location of measuring stations. Thus, pre-transition, transition and fully-developed regimes are easily obtainable. (ii) The different cases of stable, unstable and straight mixing layers. (iii) The effect of initial momentum thickness (boundary layer tripping) on mixing growth and characteristics. (iv) The effect of resolution on measurements by using passive scalar and chemical reaction techniques.

The experiment will thus be focused to:

1) Improve the quality of the volume renderings. The use of a more powerful laser such as a pulsed 20-Watt Copper-vapor laser will allow shorter exposure times while filming, thus giving sharper pictures and renderings. Also the possible use of a Spin Physics Camera recording system instead of the 16mm film will allow the renderings to be more time-efficient and with better signal to noise ratio.

2) Measure the concentration field pdf. For this purpose, a very low noise camera must be used (a 2-D Amperex imaging array with a light sheet from a 1.5 Watt Nd:Yag laser, available at the High Temperature Gasdynamics Laboratory- HTGL). For statistical convergence, many frames must be acquired, corresponding to at least 100 structures for each location and case. Although acquisition can be effected with a 386 IBM compatible, the data storage and processing will probably require the use of a workstation, also available at HTGL.

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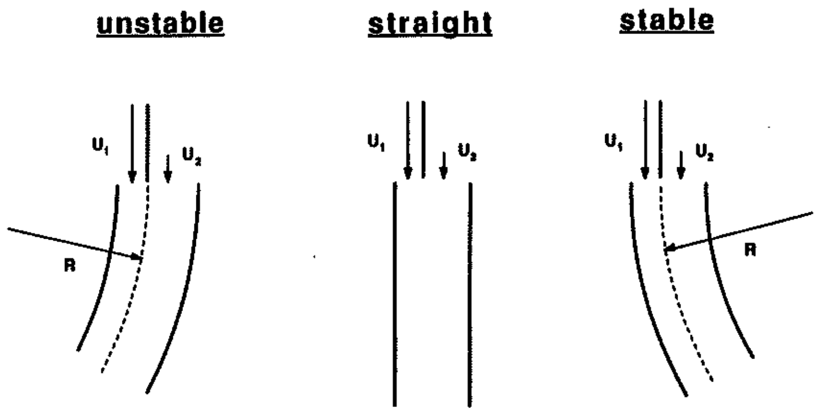


FIGURE 1. Definition of stable and unstable curved shear layers.

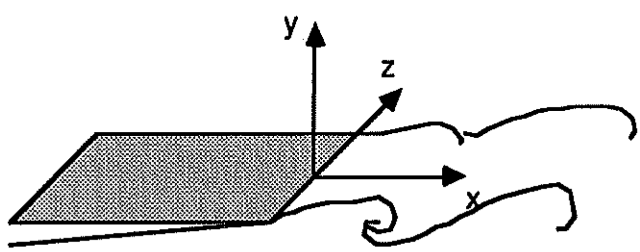
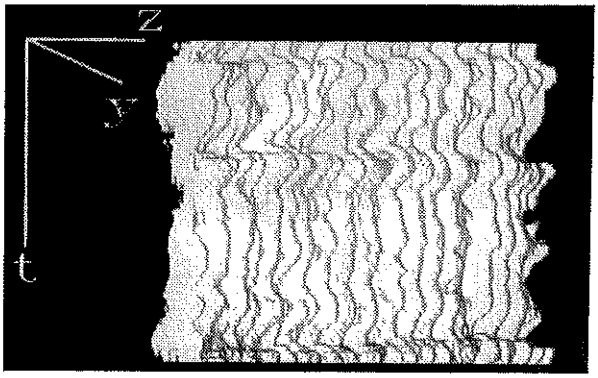
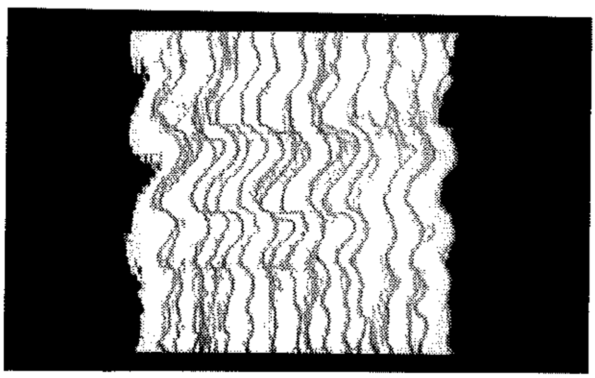


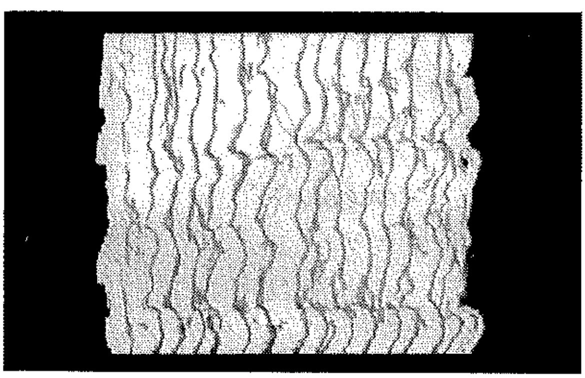
FIGURE 2. The $x - y - z$ coordinate system.



(a: unstable)

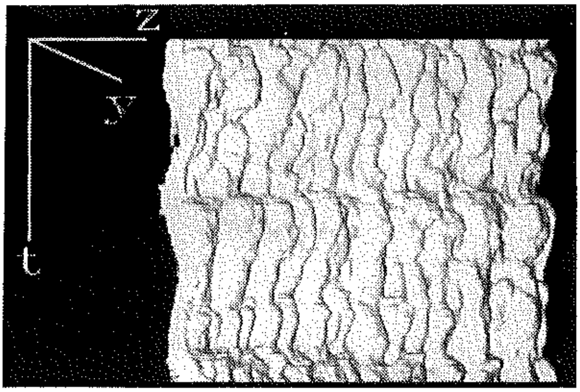


(b: straight)

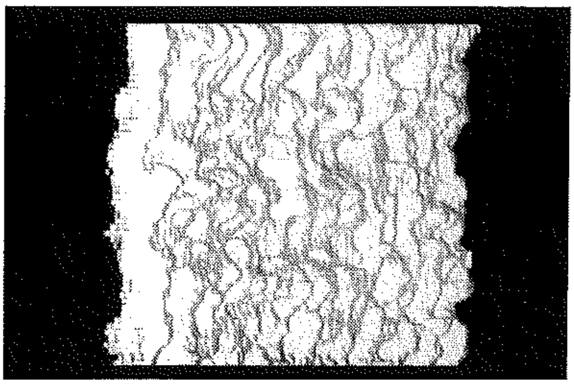


(c: stable)

FIGURE 3. Volume rendering of mixing layers at pre-transition, viewed from low-speed side ($R_e \sim 6,500$).



(a: unstable)



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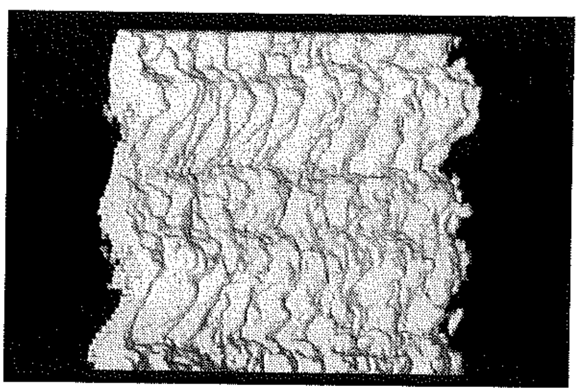

(c: stable)

FIGURE 4. Volume rendering of mixing layers at transition, viewed from low-speed side ($R_e \sim 12,000$).