Mixing measurements of straight and curved shear layers

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1. Motivation and objectives

The structure of shear layer flows at high Reynolds numbers remains a very interesting problem. Straight mixing layers have been studied [Konrad, 1977; Koochesfahani & Dimotakis, 1986; Fiedler, 1974] and yielded information on the probability density function (pdf) of a pasive scalar across the layer. Konrad, 1977, and Koochesfahani & Dimotakis, 1986, measured the pdf of the mixture fraction for mixing layers of moderate Reynolds number (*Re*) of about 25,000 (*Re* based on velocity difference and visual thickness). Their measurements showed a "non-marching" behaviour of the pdf (central hump which is invariant from edge to edge across the layer), a result which is linked to the visualizations of the spanwise Kelvin-Helmholtz (K-H) instability mode. Similar measurements at higher Reynolds numbers remain an open question: a "marching" behaviour of a passive scalar pdf at higher *Re* (Batt, 1977) suggests either resolution problems of the measurements or a change in the physical mechanisms of entrainment and mixing with increasing Reynolds number. Our work seeks to address this issue. Finally, the shear layer is known to be very sensitive to its initial conditions, which vary with different facilities.

A secondary instability mode, the Taylor-Görtler (T-G) instability, which is associated with streamwise vortical structures, has also been observed in shear layers [Breidenthal, 1978; Lasheras & Choi, 1988]. In shear layers curved in the streamwise direction when the high-speed stream is on the inside of the bend, the T-G is enhanced, whereas when the high-speed stream is placed on the outside of the bend, the T-G is suppressed, thus providing an environment for studying the outcome of the competition of the K-H with the T-G instability modes. Mixing enhancement may occur in a curved layer that enhances the T-G mode [Plesniak & Johnston, 1989]; also, the layer appears to grow about 50% thicker with an enhanced T-G mode [Karasso & Mungal, 1989]. The present work will document changes to the pdf when streamwise curvature is present.

In the present study, we are interested in measuring the concentration pdf of mixing layers spanning the Reynolds number regime from 25,000 to about 90,000. The studies will occur in curved as well as straight layers so that firm conclusions can be reached about the effect of the two instabilities on the development of mixing layers and the effect of curvature on mixing efficiency. Finally, the issue of how resolution affects the outcome of a pdf measurement will be addressed via chemical reaction techniques and via relative resolution changes of acquired data.

2. Accomplishments

2.1 Experimental facility

The facility used is a blow-down water channel described in Karasso & Mungal, 1989. It is capable of achieving a high-speed stream velocity of 2 m/s, translating to a $Re \sim 90,000$. The nominal speed ratio between the two streams is 4:1 but can be changed to any other ratio, thus allowing us to duplicate running conditions of other experimental facilities.

2.2 Experimental technique

The planar laser-induced fluorescence technique (PLIF) is used to acquire well-resolved quantitative images of the concentration field. The low-speed stream is marked with a fluorescent dye (sodium fluorescein). A very thin (approximately 300 micrometers) laser sheet is generated from a 1.5 W Nd:Yag laser. The fluorescence signals produced are recorded on a 2-D CCD array (Amperex or Cohu). The images are then acquired and stored on a 386 compatible computer. About 100 images are acquired from each run-condition, which are then processed and treated statistically to obtain the pdfs across the layer.

2.3 Calibrations and results

The choice of using a pulsed laser was made on the basis of improving the temporal resolution of our measurements. Each pulse has a duration of about 10 ns; the fluorescence lifetimes are approximately of the same order. The smallest fluid mechanics scale is on the order of microseconds; hence our images can be characterized by superior temporal resolution.

CW lasers have been used in the past with the same fluorescent dye: for those systems, calibrations of the fluorescence signal intensity with dye concentration (the quantity that is ultimately measured) exist. For our system, no such calibrations exist. Furthermore, since the peak power density of the present laser is orders of magnitude greater than that of CW lasers, the properties of the dye as a function of laser energy must be accurately measured. The latter is also necessary since the laser sheet that is formed has a Gaussian fall-off of intensity from its middle portion to the edges.

Calibrations of fluorescence signal vs. dye concentration have been made at a given laser energy level. Figure 1 shows that the response is linear, at least for the range of concentrations that we will be implementing in our studies. Light absorption and camera noise considerations will determine the final optimum maximum concentration [Pringsheim, 1949].

Energy calibrations are more difficult. The signal change along a line depends on absorption and on energy response. Furthermore, erroneous conclusions could be reached if photobleaching occurs, especially if it is exactly proportional to dye concentration for the range of concentrations that are being examined. At this point we are conducting multiple tests in that direction to discern the various effects. It is almost certain that at high energies the fluorescence signal is not linearly related to energy; this is not a problem though if absorption is ruled out. At lower energy, linearity seems to prevail. The final answer on this issue will occur in the very near future.

Preliminary runs of the straight layer have been made. A typical image is shown in figure 2. Flow is from top to bottom, and the actual size of the imaged region is 5x7 cm. A perpendicular cut through the structure shows the intensity distribution across the layer (figure 3). The strong ramp from one side to the other is counterintuitive to the idea of a non-marching pdf. A streamwise cut is depicted in figure 4. More of these cuts for various Re must be obtained for fair comparisons. A first attempt of calculating the concentration pdf for the case of $Re = 40,000$ has yielded a marching type pdf. However, we are not sufficiently sure of this result until all outstanding calibration issues have been resolved.

Once our pdf measuring technique is firmly established, we shall be measuring the pdf for the straight layer from low to high Re. These pdfs will then become the comparison for similar measurements for the two cases of the curved layer. It should then be possible to provide quantitative measures of the changes to mixing that result from the competition between the T-G and the K-H instabilities.

3. Future plans

The future plans for this experiment include: i) The completion of the current measurements for comparing the straight to the curved layers. ii) The use of chemical reaction techniques (acid-base reactions that create a threshold for fluorescence to occur) to accurately specify the amount of product in the mixing zone and also to examine the effects of resolution on all of the above measurements. iii) The effect of the initial momentum thickness on the development of the shear layer. This will be effected by tripping the boundary layer on the splitter plate at the high-speed stream.

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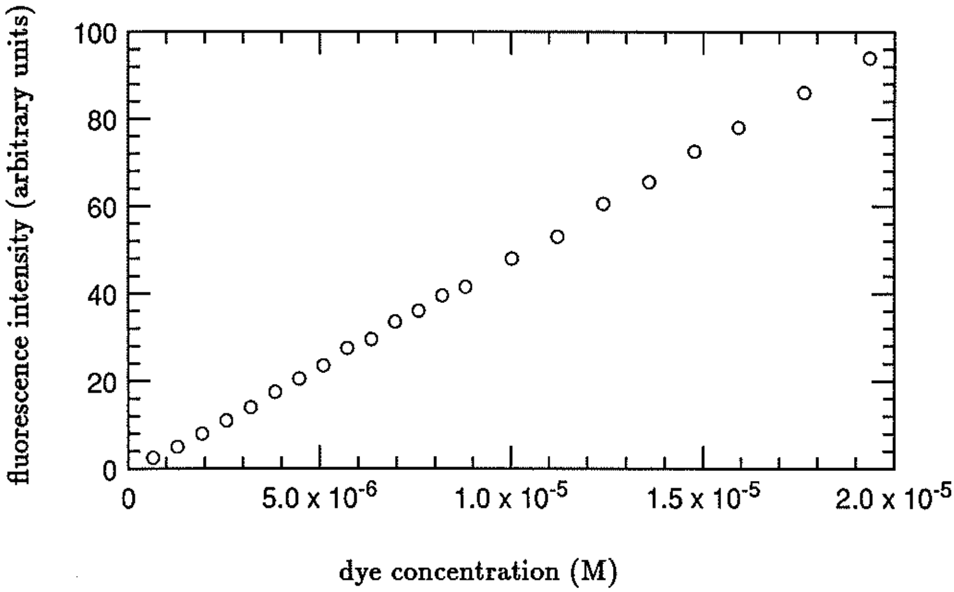

FIGURE 1. Calibration for dye concentration

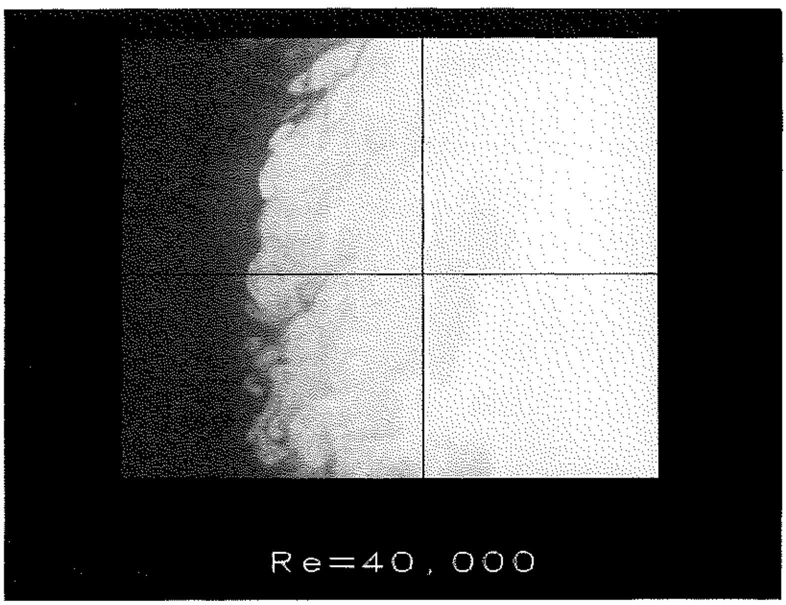

FIGURE 2. Straight layer.

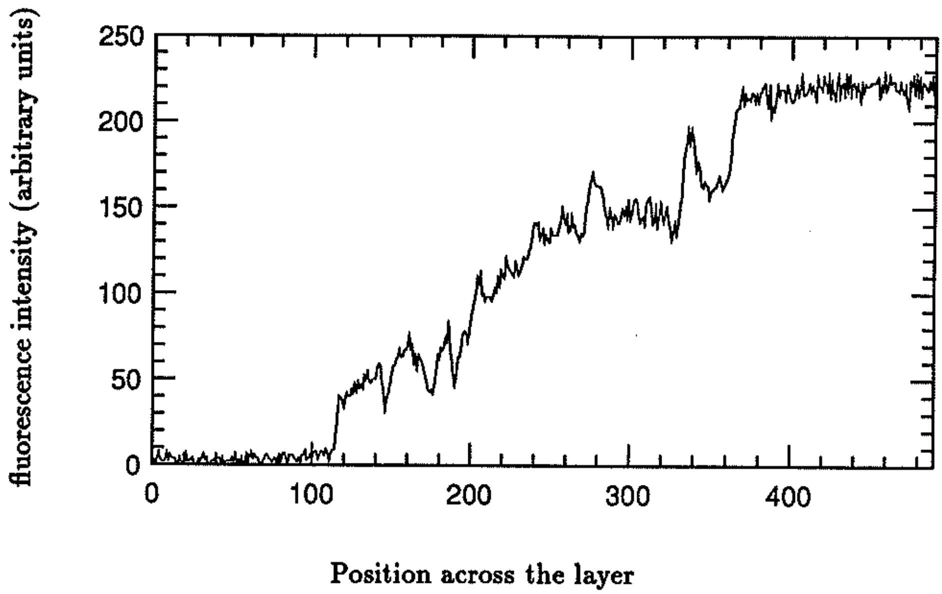

FIGURE 3. Intensity distribution across the layer.

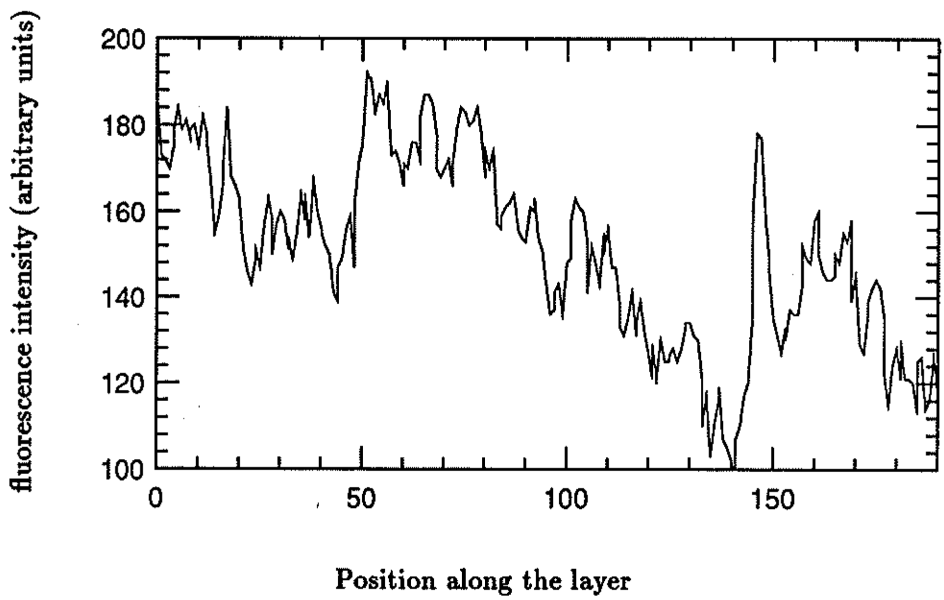

FIGURE 4. Streamwise intensity distribution.