MEASUREMENTS ON THE MIXING OF A PASSIVE SCALAR IN A TURBULENT PIPE FLOW USING DPIV AND LIF

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ABSTRACT

In order to gain a better understanding of the mixing process, simultaneous measurements of velocities and concentrations would be helpful. Therefore experiments were carried out by means of simultaneous PIV and LIF measurements on the mixing of a point source placed at the centreline of a turbulent pipe flow. The PIV and LIF measurements do not influence each other. The results are used to determine the concentration velocity correlation term present in the time averaged Reynolds equation of the concentration field. In addition we study the effect of coherent structures on the mixing process. This can be done by doing conditional averaging of the time series.

INTRODUCTION

Mixing is one of the fundamental properties of turbulence and it has many applications in science and engineering. Points of interest from a point of view of studying turbulent mixing are: maximum concentration levels, micro mixing in relation to chemical reactions, and the influence of coherent structures on mixing. The mixing process can be described as the interaction between a flow and a concentration field. The flow field follows from the Navier-Stokes equation, and is in many cases independent of the concentration field, whereas mass transport can be described in terms of a conservation equation where the molecular diffusion is usually modelled.

Consider the case of a fully developed turbulent pipe flow. The Reynolds decomposed equation for the concentration then reduces to:

$$-\overline{u}_x \frac{\partial \overline{c}}{\partial x} = \frac{\partial \overline{u'_x c'}}{\partial x} + \frac{1}{r}\frac{\partial r \overline{u'_r c'}}{\partial r} - \mathcal{D}\left\{\frac{\partial^2 \overline{c}}{\partial x^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \overline{c}}{\partial r}\right)\right\}, \tag{1}$$

where $\overline{u}_x$ is the mean axial velocity component, u'_x is the fluctuating axial velocity, u'_r is the fluctuating radial velocity, $\overline{c}$ is the mean concentration and c' is the fluctuating part of the concentration field.

As can be seen, this equation contains two correlation terms between velocity and concentration fluctuations, that include radial and axial velocity components. To study these terms experimentally it is necessary to obtain simultaneous measurements of velocity and concentration fields. This type of measurements is the objective of this study. To measure the correlation terms in (1) we apply Particle Image Velocimetry [1] for the observation of the two velocity components, whereas the concentration field is measured with Planar Laser Induced Fluorescence [2]. In our experiment these two techniques are combined and applied simultaneously to a steady and axisymmetric turbulent pipe flow with a scalar point source at the centreline. The results will be compared with the results of a direct numerical simulation (DNS) and can for instance be used for validation of PDF-models.

Before we can use these measurements to study turbulent mixing, we should first check whether the PIV and the LIF measurements do not influence each other, and determine the accuracy of our observations. The accuracy of the measurements can be estimated by measuring the mean velocity and concentration profiles, which appears on left hand side of equation 1, and compare them with the measured turbulent fluxes present on the right hand side of this equation. As our measurement technique is in principle two-dimensional, an axisymmetric flow is an ideal test case for the evaluation of this combined measurement technique, because in that case we are able to measure all terms present in equation 1. After we have determined the accuracy of our measurements, they will also be used to study the effect of coherent structures on the mixing process.

MEASUREMENT METHODS

Particle Image Velocimetry (PIV) is used to measure the instantaneous velocity field in a planar cross

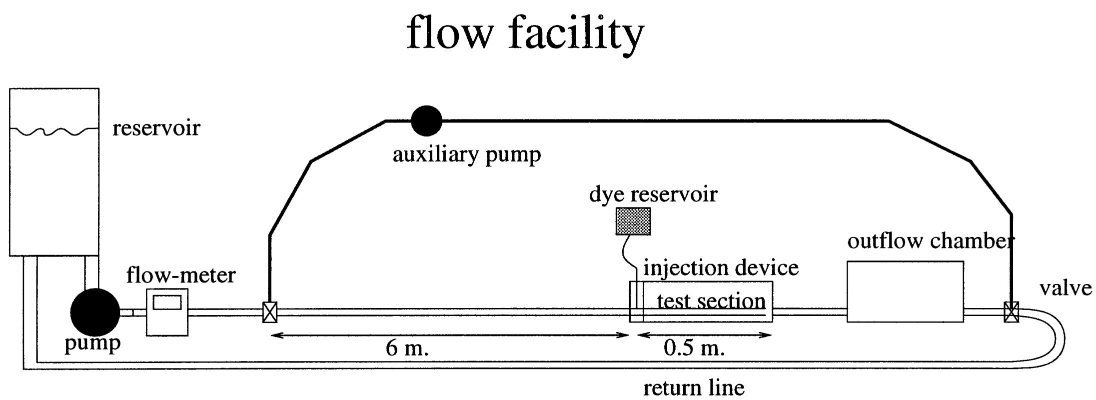

Figure 1: A overview of the flow facility used. (not to scale)

section of the observed flow. With PIV the fluid velocity is determined by measuring the displacement of small tracer particles over a small time interval. The particles have to be small so that they follow the flow accurately. To measure the particle displacement the particles are illuminated two times with a laser light sheet. The two exposures are recorded by means of a high resolution CCD sensor array. Each image frame collects both exposures. Given this doubly exposed picture the autocorrelation of the image is computed in small areas, so-called interrogation windows. The off-centre peak in this autocorrelation determines the particle displacement. In our flow all displacements have the same sign and overlapping of particle images only occurs near the pipe wall. Hence no image shifting is required for resolving the directional ambiguity that occurs for doubly exposed PIV recordings. Sub-pixel displacements are estimated using a Gaussian peak fit through the displacement-correlation peak in the auto-correlation function [3]. The time interval used in the measurements presented is 3 ms. The Kolmogorov time scale of the flow is 50 ms, so the velocities are measured practically instantaneous.

For measuring the concentration distribution planar Laser Induced Fluorescence (LIF) is used. The concentration of a fluorescent dye is observed by measuring the amount of light emitted by the dye when the dye is illuminated by a light source with known intensity. The amount of emitted light is measured with a CCD camera. The intensity of the light source is measured by recording the emitted light intensity distribution of a uniform concentration field. This is done in the same setup in which the measurements are done. To determine the light intensity distribution we record 50 images and average them for each pixel. Besides that a series of 50 dark images is recorded to determine the grey value offset for each pixel. Subtracting the dark grey value distribution from the grey values obtained from the uniform concentration gives an estimation for the light intensity distribution of the light sheet. Finally, the concentration distributions are measured by recording an image, subtract the dark grey value distribution and normalise the result with the light intensity distribution obtained by the method described above. The exposure time of the measurements is 1.5 ms, which is again much smaller than the Kolmogorov time scale, so also the concentration fields are frozen.

During the combined measurements first a PIV image, then a LIF image is recorded. The two images are taken within 6 ms, which is well within a Kolmogorov time scale, and can therefore be seen as recorded simultaneously. To determine the fluctuating components of the measured quantities an ensemble average of a series of measurements is subtracted from the frames. In this way the instantaneous fluctuations of the velocities and concentrations can be computed.

EXPERIMENTAL SETUP

To be able to do these measurements, an experimental facility was designed and constructed. The flow facility consists of a 6 meter long perspex pipe with an inner diameter of 50 mm and a wall thickness of 5mm. In the pipe an injection device for fluorescein is mounted. The injection mechanism consists of a syringe driven by an electro motor. The syringe is connected to a thin needle with an inner diameter of 0.8 mm and an outer diameter of 1.0 mm. The needle is mounted at the centreline of the pipe. A separate section for the PIV and LIF measurements is mounted just behind the injection mechanism. In this measurement section the pipe wall is replaced by a thin glass cylinder, with a wall thickness of 1.8 mm, placed in a rectangular box filled with water and with glass windows. This reduces the optical aberrations by the curved pipe wall far below the measurement accuracy in the centre region of the pipe. An overview of the total setup is given in Figure 1.

The reservoir and the return line can be short cutted. In this way a flow system is created with a small system volume. This system is used for the LIF calibration. The loop is filled with fluid with known fluorescein concentration to be able to measure the light intensity distribution of the light sheet.

The experiments are done in water, where fluorescein is the scalar with a Schmidt number (i.e the ratio of kinematic viscosity to molecular diffusion) of 2075. This means that the time scale of the molecular diffusion is much longer than the time scale of the turbulent mixing. The diffusion terms in (1) can therefore be neglected at short distances of the injection point. Except for a small disturbance due to the injection mechanism, the flow can be considered as a fully developed turbulent pipe flow with a steady and (nearly) axisymmetric mean flow field.

For the illumination of the PIV images a twin Nd:YAG pulsed laser system (Spectra Physics PIV 400) was used. A frequency doubler is used to convert the 1064 nm laser beams to visible 532 nm laser beams. The lasers have a fixed pulse rate of 30 Hz, with an adjustable time separation between the pulses of each laser. The lasers have a beam diameter of approximately 6 mm. The wavelength of the light from the Nd:YAG lasers is outside the absorption band of the fluorescein (see fig. 2), hence the Nd:YAG laser do not induce fluoresence.

The light source for the LIF measurements is the 488 nm line of an Argon-ion laser. This wavelength is selected because it is very close to the position of the peak in the absorption spectrum of fluorescein (see figure 2). The beam of the Argon-ion laser, which has

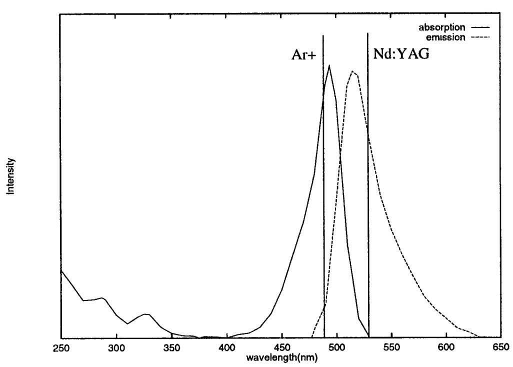

Figure 2: The absorption and emission spectra of fluorescein.

a beam diameter of 1.5 mm has to be expanded to be able to combine it with the YAG beams. The PIV and the LIF measurements can be done with help of a 992 × 1004 pixel camera. The cameras (Kodak ES 1.0) can be operated in 'free run' at a frequency of 29 Hz or externally triggered with any frequency between 0 and 30 Hz. To obtain good statistics of the velocity field, the cameras were operated at a low frequency. During the combined velocity/concentration measurements, the cameras were operated at 30 Hz.

The cameras are connected to Datacube MV200 pipeline processors, which read out the cameras and store the frames in a RAM of 256 Mb. This enables us to record 268 frames in one run. After the acquisition the frames are stored on a normal hard disk of a workstation. The workstation is used to process the raw frames.

For the combined PIV and LIF measurements the laser beams of the Nd:YAG and the Ar^+ lasers have to be combined along the same optical path and transformed into a light sheet. The setup is sketched in Figure 3. The optical setup creates a parallel light sheet with a minimal thickness. The light sheet has a Rayleigh length of 50 mm, so the light sheet is as thin as possible and almost parallel over the full pipe diameter.

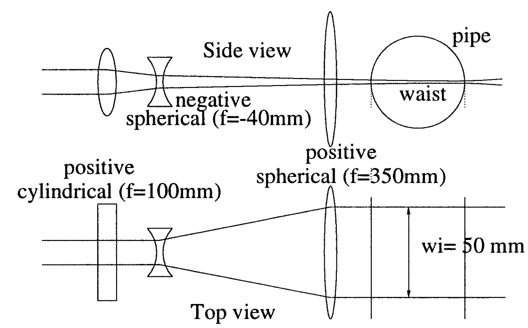

Figure 3: Top and side views of the optics used to create the light sheet.

RESULTS

The PIV system and the LIF system were tested first for a flow on which we have alternative data from other studies. This is a fully developed pipe flow at a Reynolds number of 5300, for which we have results obtained by means of LDV and PIV measurements, and results from a DNS [1]. All profiles are scaled with the friction velocity, which is in our case 6.8 mm/s. The results for mean profiles, rms profiles and the turbulent stress are shown in Figure 4. The different profiles agree within the measurement uncertainty. The results confirm that our DPIV system is able to perform accurate measurements.

Next we consider the concentration measurements. The main problem in measuring statistical properties of the concentration field is the intermittency of the fluorescein concentration. This intermittency has two reasons. The first reason is that the diameter of the injected fluorescein plume is small with respect to the pipe diameter. The second reason is the high Schmidt number of fluorescein, due to which almost all fluorescein will remain in small structures which are deformed by the flow. The result is that most images are almost completely black except for some small regions containing the concentration structures (see figure 5). This is also the explanation for the high rms values of the concentration profiles (see Figure 6).

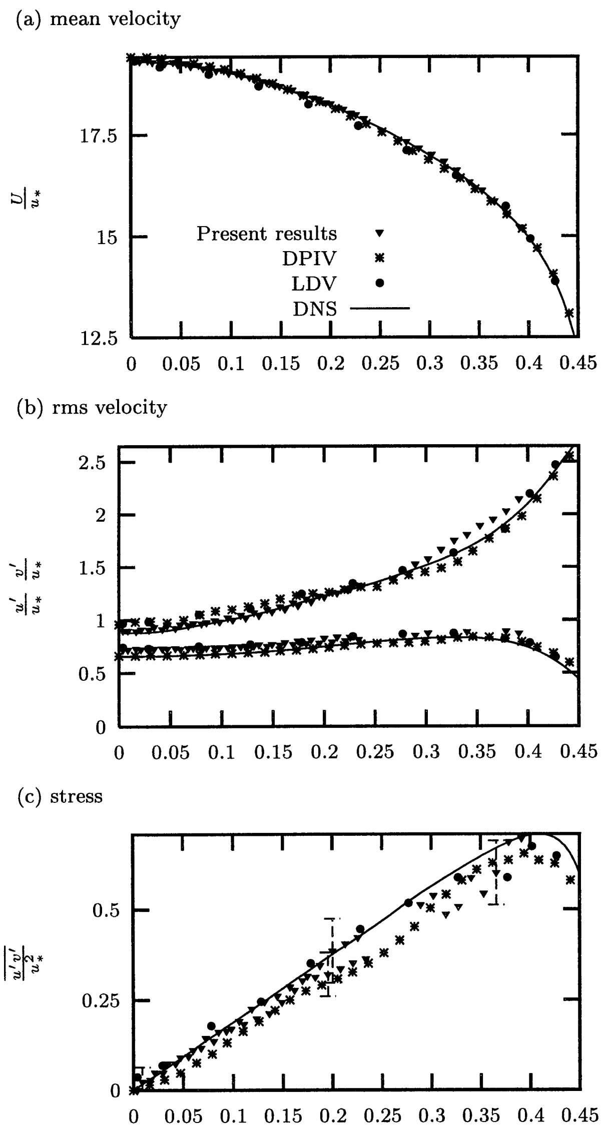

Figure 4: Statistical properties of the velocity field as a function of the radial distance from the centreline: (a) mean axial velocity, (b) axial (u') and radial (v') velocity fluctuations; (c) Reynolds stress ($\overline{u'v'}$). All data are compared with a DNS, DPIV data and LDV data. [1]. All velocities are scaled with the friction velocity u_*.

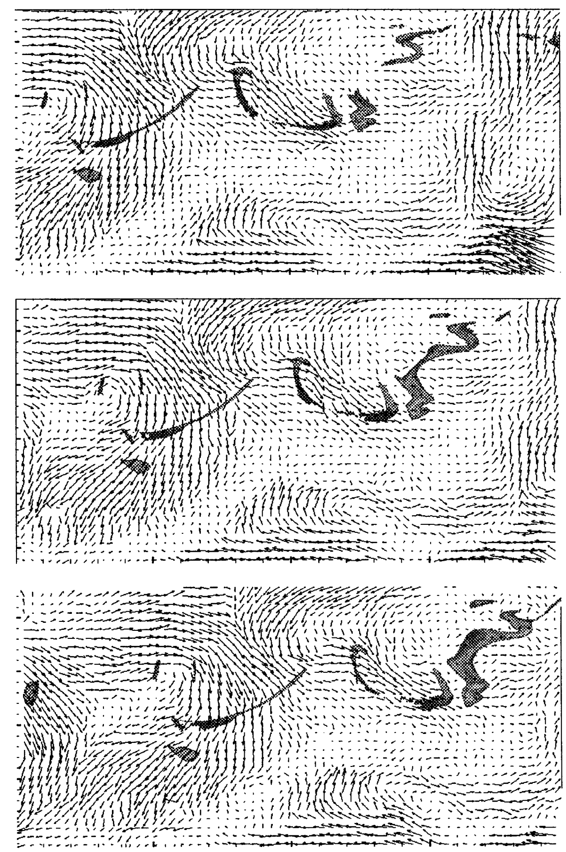

Figure 5: A small series of combined PIV-LIF measurement. The flow is from left to right. The length of the domain shown is 45 mm.

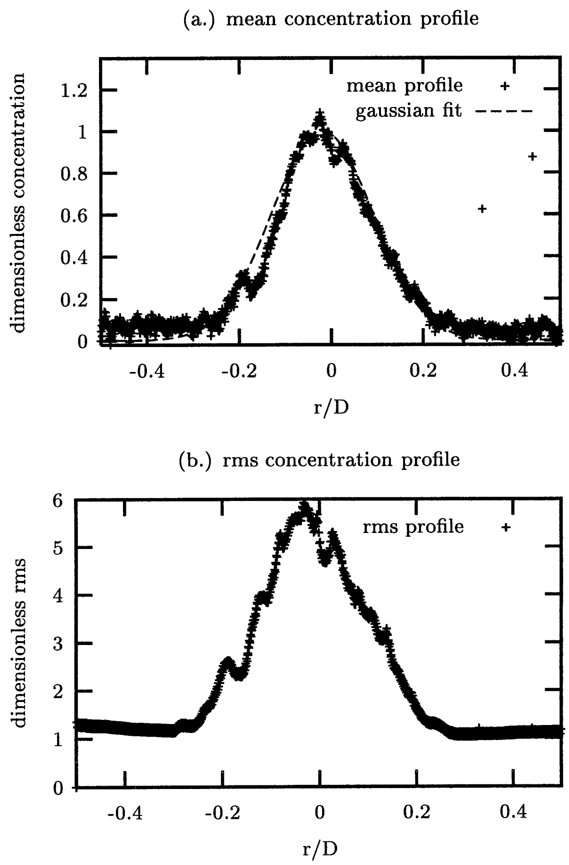

Figure 6: The statistics of the dye concentration at 3 pipe diameters downstream of the injection device. Concentrations are normalised by the fitted maximum mean concentration at the measurement position: (a) mean concentration, (b) RMS concentration.

In figure 7 the centreline concentration between 0.5 and 2.5 pipe diameters downstream from the injection point is shown. As can be seen the concentration decays as $1/x^2$.

COMBINED PIV/LIF MEASUREMENTS

Combined PIV/LIF measurements have been done at distances ranging from 0.5 to 5.5 pipe diameters behind the injection point. The measuring area of the measurements is 0.9×0.9 square pipe diameter. At each position 12 series of 134 frames were recorded. The frame rate used was 30 Hz. In figure 8 the measured velocity statistics at a distance between 2.5 and 3.5 pipe diameters downstream of the injection point are shown. The small asymmetry of the velocity profile is caused by the wake behind the vertical part of the injection needle. In figure 9 the measured velocity/concentration correlations are shown at two positions. At the position close to the

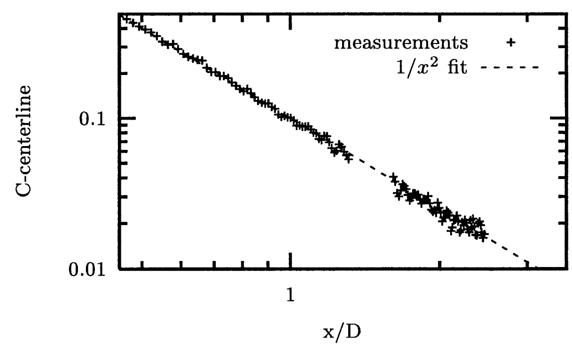

Figure 7: The centreline concentration as function of the distance from the injection point.

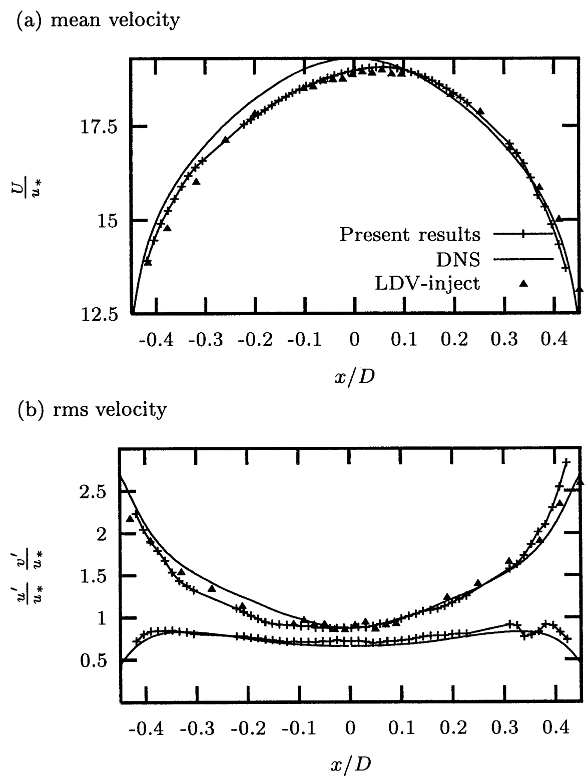

Figure 8: The velocity statistics of the flow measured at a distance between 2.5 and 3.5 pipe diameters behind the injection point. In (a) the mean velocity profile is given. In (b) the axial (upper curve) and the radial rms velocities (lower curve) are shown.

injection point the resulting predicted mean concentration gradient in the axial direction is qualitatively the same as the measured concentration gradient.

To be able to present better statistics more measurements need to be done. As discussed above the convergence of LIF data is slow due to the intermittency of the fluorescein concentration.

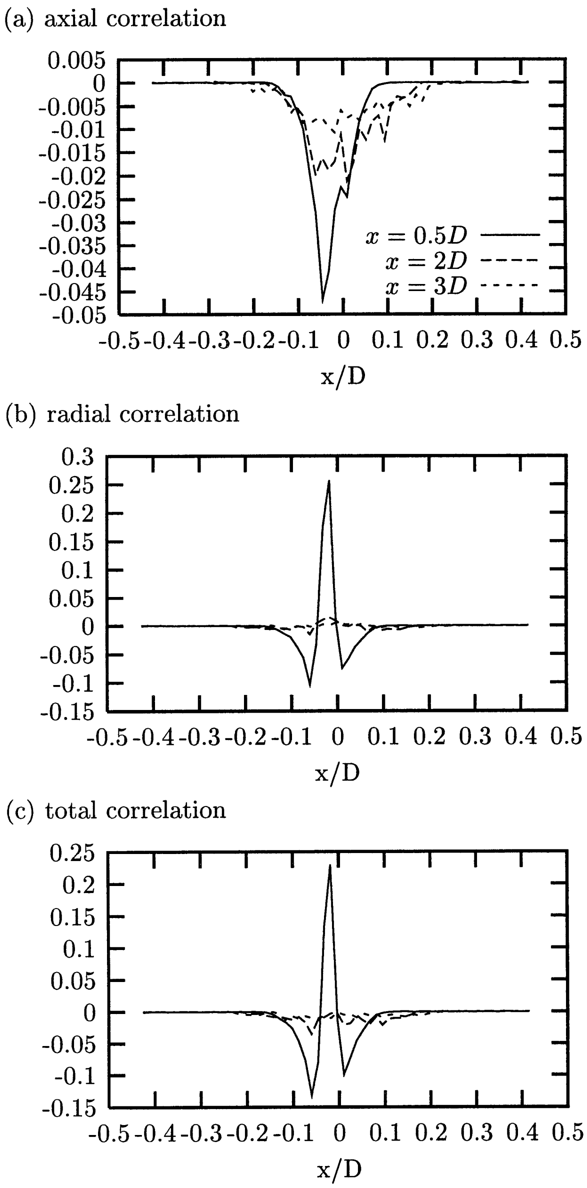

Figure 9: The cross correlation terms present in the Reynolds decomposed averaged mass transport equation at three distances from the injection point. The curves in figure (a) show the axial correlations, in (b) the radial correlations are shown and in (c) the sum of the two terms is plotted.

CONCLUSIONS AND FUTURE WORK

DPIV and LIF measurements were applied simultaneously to study mixing in a turbulent pipe flow. The results for the velocity measurements are found to be accurate within 0.8% of the mean velocity. The results for the concentration measurements are influenced by the intermittency of the fluorescein concentration which leads to large statistical errors.

Now it is clear where the limits of the combined measurement techniques are, off-axis injection experiments will be done. This will give us information on the effect of shear on the mixing process. In the future we plan to do measurement on the mixing of a reacting scalar. This can be done by using the pH-dependency of the fluorescence of fluorescein. The mixing of two point sources can be studied by injecting fluorescein solved in acidic fluid at one point and alkaline fluid at an other position. Fluorescence will only occur at the placed the two point sources have been molecularly mixed [4] [5].

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