On high spatial resolution scalar measurement with LIF

Part 2: The noise characteristic

G. R. Wang, H. E. Fiedler

Abstract A spatial resolution of about 4 (μm)$^3$ for scalar measurement in turbulent mixing with Laser-Induced-Fluorescence is realized in this experiment. It is shown that for the high spatial resolution the signal is weak because of the measuring volume is very fine. The corresponding main problem is that the signal to noise ratio is small, especially for the high frequency signal corresponding to small structures. It is shown that the dominating noise is the shot noise in the signal from the photomultiplier tube. The measurement results indicate that an increase of the signal level through the increase of dye concentration and/or laser power is limited, mainly due to thermal blooming and photobleaching.

List of symbols

- $C$: laser dye concentration, M
- $D_p$: pipe inner diameter
- $d_l$: laser focus diameter
- $f$: signal frequency
- $f_l$: lens focus length
- $I_{\text{rms}}$: RMS of $i_d$
- $I_f$: fluorescence intensity
- $I_{0}$: incident laser intensity
- $I_{\text{rms}}$: RMS of Johnson noise
- $l$: length of light path
- $P_l$: laser power, W
- $Q_f$: fluorescence quantum yield
- $U_1$: high fluid velocity of mixing layer
- $U_2$: low fluid velocity of mixing layer
- $U$: average fluid velocity
- $V$: measuring volume
- $\Delta f$: frequency bandwidth
- $\lambda_w$: wave length of light
- $\sigma$: absorption cross section

1 Introduction

High spatial and temporal resolution measurement of turbulent mixing is important both in physics and engineering. For physics, the study of statistical properties of small scale structures is a very active field in order to find a universal law in turbulence which could also be used in other fields (for example in economics). Here, not only the small structures of velocity and vorticity are of interest, but also that of scalars in turbulent flows. For engineering, the actual reaction rates of the fast chemical reactions in turbulent flows, which emerge in chemical engineering, combustion and environment depend closely on the statistical properties of small scale structures in the flow. The smallest scale of scalar can be Obukhov-Corssin scale when fluids physical propery Schmidt number Sc $\sim 1$ or Batchelor scale when $Sc \gg 1$. The Obukhov-Corssin scale size is the same order of Kolmogorov scale and Batchelor scale is much smaller than Kolmogorov scale (see for instance Baldyga and Bourne (1986), Villermaux (1986)). The Batchelor scale can be very fine, say, of the order of 0.1 $\sim 10$ μm in water flows depending on the flow itself and on Schmidt number. If the spatial resolution is not high enough (i.e. the measuring volume is larger than the smallest scalar scales in the flow), some physical details will be lost and this in turn obstructs the understanding of the physical process.

Laser-Induced-Fluorescence (LIF) is the best non-intrusive method used nowadays, for high spatial resolution measurements of concentration in turbulent flows. Until now the highest spatial resolution realized (which is really measured), is, to our knowledge, of the order of 40 $\sim 60$ μm (Miller, 1991). This, is much larger than the smallest scalar scales. Therefore, the above mentioned small scale is difficult to measure directly. The fine focusing of the laser beam in fluid mechanics is not as easy to achieved as it is done in micro-optical and electronic...

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technology, since in the former the working distance is much longer.

LIF is a relatively new method although it is rapidly spreading now in fluid mechanics. Still, there is a relatively limited number of articles on the method of LIF itself compared with, say, Laser-Doppler-Anemometer (LDA). For instance, there are few papers dealing with its signal to noise ratio (SNR), except the related works from Koochesfahan and Dimotakis (1985), Guillard et al. (1998).

This paper deals with SNR of high spatial resolution scalar measurement with LIF for the study of turbulent mixing. It was initially believed that the fine focusing of the laser beam is the most difficult task for high resolution measurement. However, having achieved very fine focusing of around 4 μm we found the signal level to be very low, because of the small measuring volume. This results in low SNR, especially for the high frequency region where signal amplitude is also small. Furthermore, it turned out that the signal can not be simply increased by increasing the dye concentration and the laser power input because attenuation, photobleaching and thermal blooming would contaminate the signal (Wang and Fiedler, 1999). It is expected that this is also a crucial point for high spatial resolution measurement of all measuring techniques based on light scattering. In correspondence with Wang and Fiedler (1999) the expressions for laser power, $P_l$, and laser intensity, $I_l$, are used in this paper.

## 2 Experimental set-up

The schematic of the experiment is displayed in Fig. 1 and was described in Part I (Wang and Fiedler, 1999). Here, we need to give some extra description. At the measuring point there is a water vessel with a window made of quartz glass, which is used to prevent refractive distortions from air to the plexiglas pipe and water. Since the optical quality of the thick plexiglas wall of the pipe is rather poor and its refracting index is not exactly the same as of water, there is a window at the measurement point of the pipe which is replaced by a plastic sheet of the kind used for overhead projectors with thickness 0.17 mm. The transparency is sealed with Sikaflex-260. This enables better focusing of the laser beam. A detailed description of the channel is given in Wang (1999). Disodium fluorescein is used as laser dye for fluorescence.

The laser is a Coherent Inova 90 with a power of 5 Watt. The laser light is composed of blue (488 nm) and green (514 nm) light and is adjusted to TEM$_{00}$ mode. Since the fluorescence emission spectrum is strong at 514 nm, and thus the scattered laser light (514 nm) from the particles in water can cause noise, only the blue color light is used as exciting light and an optical filter is placed at the output of the laser, which only passes the blue light.

In this experiment, the maximum input light power is estimated from measurement to be of the order of $10^{-10}$ W. To achieve a frequency bandwidth of 100 kHz, which is the order of frequency of the very small scales, i.e. in the range of Batchelor spectrum, a photomultiplier tube (PMT) is used. To reduce dark noise, a PMT R6060-2 with peltier and heat sink from Hamamatsu is used here under cool condition. The output current from the PMT is very small and is amplified by a current amplifier to match the ADC input range and get a better resolution. To make sure that no extra noise comes from the amplifier, a low noise current transimpedance amplifier with transimpedance (gain) of $2.5 \times 10^6$ V/A and frequency bandwidth of 280 kHz was constructed. According to our test, to get 100 kHz real dynamic signal without the 3 dB loss of its amplitude, the bandwidth of the amplifier was set at 280 kHz. The noise current from the amplifier is only about $100 f A/Hz^{1/2}$ (it was measured by Femto Mess-technik GmbH). It consists of two operational amplifiers in series. Figure 2 shows the diagram of the amplifier used. The first is inverse amplified through JFET of LF657, because of its low input noise current. The second is non-inverse with OP37, because of its low input noise voltage. The feedback resistance is high enough so that the Johnson noise is much smaller than dark noise. The dark noise and Johnson noise from the amplifier and the PMT was found to be negligible (see Sect. 5).

The noise from the PMT has a very wide frequency bandwidth, especially for frequencies higher than 100 kHz. The maximum frequency which can be measured in this system is 125 kHz. Thus, a low pass analog filter is needed. This filter is used for two reasons: to eliminate the high frequency noise from the PMT and as anti-alias for the ADC. To get real time trace signal, it is expected that the filter should have small phase distortion and high attenuation rate (rolloff). For this aim, two 4th-order analog low pass Bessel Filters EWR-3-4-BE-T/S from MessTeam are used in series to obtain a 8th-order filter. The cut-off frequency range is from 10 Hz to 999 kHz. With the low