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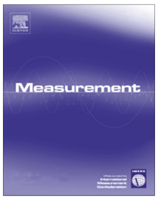

Calibration of a planar laser induced fluorescence technique for use in large scale water facilities

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ABSTRACT

A calibration process for planar laser induced fluorescence (PLIF) is presented and employed to investigate the mixing field of a co-flowing jet in a water channel flow. The calibration technique uses individual calibration curves for each pixel in the image array that correct for the non-uniformities of the laser sheet, optics and digital sensor and account for parameters that affect fluorescence efficiency of the dye. A unique commercial optic is introduced into the optical train to generate a thin laser sheet with an approximately uniform laser intensity distribution. The performance of the calibration procedure is investigated by analysis of the calibration data and through the investigation of a co-flowing jet. The results compare well with the results documented in the literature for this flow field. The work shows that the simple approach designed specifically for application in large-scale facilities is suitable for calibration of PLIF style techniques.

1. Introduction

In industrial applications, jets are often used to introduce and control the mixing of one fluid into another. Jets in a co-flow have been extensively studied experientially and numerically, with only a small sample of the existing literature cited here [1–5]. Predominately the velocity field has been investigated with the aim to develop simple scaling models of the flow. An understanding of the scalar field of concentration is important when investigating a mixing process, though this is difficult to determine when the scale of the jet flow, the flow field of interest or flow facility itself is large.

A useful and powerful technique for studying turbulence and mixing in free shear flows such as jets is laser induced fluorescence (LIF) [6] and its planar variant (PLIF) [7] which are spectroscopic techniques commonly used in quantitative measurements of concentration. In the PLIF process, a fluorescent dye is used as a fluid tracer and a laser is used to excite the dye in a plane using a laser sheet. As the dye de-energies from its excited state, fluorescing photons are emitted that are captured by a 2D imaging sensor. The number of photons collected is correlated to the concentration of the dye in the marked fluid and a 2D image of the concentration field is generated. The earliest works demonstrated the applicability of LIF to obtain quantitative information of the scalar concentration field [6–8] and PLIF has become popular within the fluid dynamics community. It has been commonly used in qualitative and quantitative analyses of mixing and of the structures and dynamics of jets [9] and shear layers [10].

Overviews of the LIF/PLIF technique [6,11] have highlighted that the main factors controlling the fluoresced light intensity $I_{f(i,j)}$ at a location (i,j) in an image are,

$$I_{f(i,j)} = f(I_{l(i,j)}, C_{(i,j)}, \chi_{(i,j)}) \tag{1}$$

where $I_{l(i,j)}$ is the local intensity of the fluorescing laser, $C_{(i,j)}$ is the local concentration of the fluorescing dye and $\chi_{(i,j)}$ is a parameter that captures phenomena that affect the efficiency of the fluorescence of the dye. Properties of the dye, such as extinction efficiency, laser saturation, temperature and pH dependence affect the overall performance of the technique. In previous investigations the fluorescence

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intensity of the dye has also been found to have a dependence on the mixing characteristics of the dyed flow [12–15]. This dependence is related to the susceptibility of a dye to thermal blooming and photo-bleaching processes that are influenced by laser intensity, dye concentration, and the geometry of the measured volume [12–15]. Additionally, Crimaldi [11] showed that the method used to generate the laser sheet has a significant impact on the quality of the image collected. The performance of the detector in terms of quantum efficiency, response across the 2D array and noise characteristics have a significant impact on the counting of fluoresced photons. This brief review highlights that every component of a PLIF system needs to be considered when attempting to make quantitative scalar measurements. An important part of the experimental PLIF procedure therefore is the determination of suitable calibration and data correction processes [6,11,12–15].

Several works have described different correction and calibration processes to obtain scalar concentration from fluorescence intensity [16–18]. The most common method is to obtain the constants that relate fluorescence intensity with laser intensity and dye concentration through the use of the PLIF system *in situ* on a sample of known concentration. This method requires maintaining the same known concentration of dye at every location within the interrogation region. Consequently, all fluid for the complete flow system will also be required to have the same dye concentration, independent of the scale of the system.

Other works have identified aspects of the PLIF approach that should be addressed to obtain accurate measurements. Ferrier et al. [18] proposed a correction process for the attenuation of the laser through the region-of-interest that requires the determination of all correction parameters before every experiment and for every scan-line in the image array. A scan-line is defined as the row of pixels that is parallel to the direction of a laser ray. Ferrier et al. [18] also suggested a method to correct images for the vignette error associated with the imaging optics. This method also included a correction for errors that accumulate when converting the captured signal to a digital signal. Diez et al. [19] showed that some geometrical considerations could be used to correct images, due to the variation of the light intensity distribution in the laser sheet. The recent work of Crimaldi [11] describes a relatively simple image processing procedure that is an extension of the algorithms used by Crimaldi and Koseff [20], Prasad and Sreenivasan [21], and Koochsfahani et al. [22] and requires the calculation of parameters such as an attenuation coefficient and a concentration constant.

While the above methods have been shown to provide quantitative scalar data, these approaches are difficult to implement in large scale facilities. As an example, in a large scale water channel or flume facility, the basic methodology would call for the seeding of the entire facility with a uniform known concentration of dye and this would need to be maintained at a constant temperature and pH during the calibration. The facility would then also need to be flushed to allow the experiment to continue. This requires a significant amount of time to exchange and de-gas purified water to be used in the experiment.

The aim of the current study is to develop a process that would allow the calibration of a PLIF system *in situ* in a "large" scale water facility. A PLIF system is described along with the important features of the flow facility. A detailed description of the calibration method and an assessment of important parameters are outlined. This is followed by a brief investigation of the scalar mixing field of a co-flowing jet. The co-flowing jet system is used to highlight the performance of the calibration process by comparing results with current understanding of this flow field and results that have been presented in the literature.

2. Experimental setup

The calibration process was developed experiments to be carried out in a closed loop water channel facility that has been extensively used in the past to investigate atmospheric boundary layers and jets [23–26]. A schematic of the facility is shown in Fig. 1 and depicts a section of the channel with a co-flowing jet nozzle located on its centerline. The channel is 5.24 m long by 680 mm wide and 470 mm deep with glass sides and bottom for complete optical access to the entire test section. It has a return section and two pumps for general water flow placed in between an inlet and exit plenum that were designed to control flow profiles and water height in the working section and has a total water volume of ~5000 l. Refreshing this volume is a 2–3 day process to allow the system to drained, be re-filled and have enough time to pass to allow it to de-gas. A uniform grid was placed at the inlet of the water channel built with flat stainless steel bars of 19.2 mm × 5 mm with a total open area of 56% with a mesh spacing of 76.2 mm. This grid turbulence generates a near uniform velocity profile for the stream-wise component in the measurement test section located 3–4 m from the grid with variations found to be within 5% [23–26]. In the test section the turbulence intensity was found to be 4% of the mean horizontal velocity [23–26] which was 4.8 cm s^{-1} for all experiments presented here. A glass pane (labeled Surface Glass Screen in Fig. 1) was placed on top of the free surface to avoid any distortion due to the small waves that could appear on a free surface.

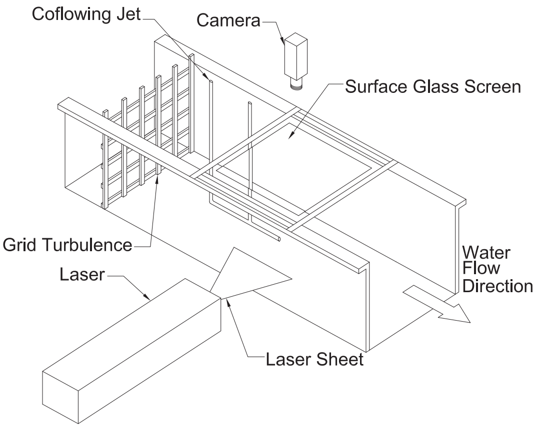

Fig. 1. Schematic of the experimental set-up of the co-flowing jet.