

Evaluation strategies for LIF-based measurements of the mixing field in a transient free jet

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Abstract

Different experimental strategies for quantitative measurements of mixing fields at transient free gas jets by means of laser-induced fluorescence are discussed. Important issues like the selection of fluorescence markers, seeding strategy, fluorescence quenching, correction of spatial and temporal variations in the laser field, and the conversion from raw signals to absolute mixture fraction values are discussed. As an alternative to conventional LIF-tracer seeding strategies, a hybrid method combining jet seeding and inverse (ambience) seeding is applied found to provide a straightforward laser-sheet correction and signal calibration.

Introduction

In many devices, ignition of combustible gas mixtures by transient turbulent hot gas jets is an important phenomenon, either for initiating a desired combustion process [1,2], or also as a major safety issue in various fields ranging from chemical industry to nuclear power plants [3–5]. In explosion protection, one possible measure is the type flameproof enclosure. Immediately after an ignition occurred inside the constant-volume containment, a flame front spreads and the pressure inside the vessel rises. Even if the combustion does not propagate from inside the enclosure to the ambience by a direct flame transmission, a re-ignition can often be observed in the head vortex of the hot free jet emerging from inevitable narrow gaps and joints (e.g. [6]). The processes leading to and taking place during ignition by hot free jets are complex. The dominating processes are chemical reactions coupled with energy and mass transport during turbulent mixing of fresh and exhaust gas. Due to this complex chemistry/turbulence interaction, their systematic experimental investigation as well as their description by numerical models (e.g. [7]) is afflicted with several challenges. In order to obtain a more systematic experimental access to the individual phenomena, measurements in simplified model systems appear to be promising. Therefore, the effects of flow and molecular transport are studied isolated from the chemical reactions in investigating non-reacting helium/nitrogen-jets impinging into a nitrogen atmosphere. Similar non-reacting studies have been conducted by [8,9].

The diagnostic scheme for this investigation is to be selected with care: The mixing field is highly transient and inhomogeneous, with small structures being present due to turbulence. The chosen technique, therefore, should be capable of high spatial resolution, and also allow to capture “short-exposure” images, with exposure times down to the fastest relevant time scales. Also, the technique should deliver good signal-to-noise ratios and allow an evaluation of the observed signals to

receive quantities related to the mixing field, e.g., the mixture fraction.

Many laser diagnostic techniques can fulfill this spectrum of requirements, and one class of techniques lends itself to this particular case, namely laser-induced fluorescence (LIF). LIF can deliver sufficiently strong signals on a 2D geometry, with signals in a spectral range that allows discrimination of signal from scattered light.

In this work, different strategies for laser-optical investigations of the mixing field at a free jet impinging into a quiescent mixture are investigated, resulting in an experimental method that combines good practical feasibility in laboratory environments with certain favorable features (like auto-calibration and a simple correction procedure for laser-sheet inhomogeneities). Although the method is applied to cold flows with non-reactive jets in this work, no obstacles exist, in principle, to an application for the reacting case, with hot flows.

Experimental Setup

In the following, a setup for spatially resolved quasi-instantaneous laser-based investigation of well-defined transient free jets is explained.

Injection system

The free jets are generated by means of a FSI-valve (fuel stratified injection) commonly used in engines with open-combustion-chamber injection with six injection openings. In order to generate a homogeneous flow and reduce the turbulence due to the injection valve, the gas is injected into a reservoir before entering a nozzle measuring a length of 70 mm with an inner diameter of $D = 1$ mm.

After having passed the injection system the free jet enters the test chamber, which is optically accessible by three quartz glass windows. At the nozzle exit, the gas pressure can be assumed to be far below the inlet pressure. The inlet pressure is the pressure at the FSI-valve, not the pressure at the nozzle exit. Inside the test vessel, the temperature and pressure can be assumed to be equal to ambient values ($T = 293$ K, $p = 1$ bar). In order to mimic exhaust gas jets at different

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temperatures, the density of the gas mixture varies. Within this study, the helium to nitrogen ratio was chosen in a way as to mimic an exhaust gas temperature of around 1400 K (95 vol.-% He, 4.8 vol.-% N₂, 0.2 vol.-% NO). The test chamber has been built quite large (volume 0.012 m³), to prevent influence from the chamber walls. More detailed information on the test vessel can be found in [10].

Laser system

Figure 1 shows the laser-setup. A frequency-tripled Nd:YAG laser (InnoLas) is used to pump a dye laser

(LaVision) has a resolution of 54.71 μm per pixel. A pulse generator (Quantum Composers, Model 9514) synchronizes the temporal input signals for the single components FSI-valve, camera and laser.

Diagnostic issues

When investigating unsteady, high-speed flows, planar laser induced fluorescence (PLIF) with pulsed lasers is very often used. With this laser diagnostic technique, a specific absorption line of some molecule present in the investigated flow is excited by means of a pulsed laser. The resulting emitted fluorescence light is

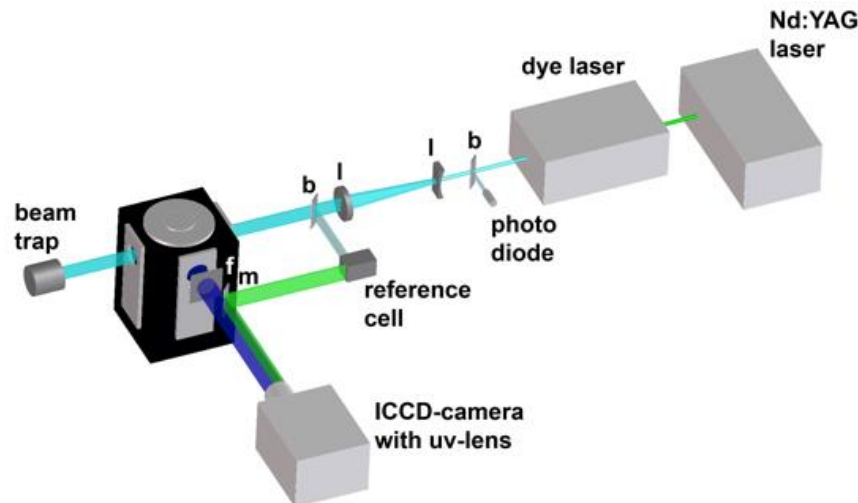


Fig. 1 Sketch of the experimental setup (b: beam splitter, l: lens, m: mirror, f: filter).

(Pulsare, Fine Adjustment, Coumarin 2). A laser light sheet is formed from the dye laser beam (near 226.7 nm) by means of a cylindrical lens with a focal length of -41 mm (uv λ 257 nm) followed by a focusing lens system with a focal length of 500 mm. The laser energy is qualitatively monitored using a photo diode (Hamamatsu S12271). The sheet thickness was determined to be $0,2 \pm 0,05$ mm. A usable sheet height of 30 mm was obtained for the measurements. In order to account for the shot-to-shot laser energy variation as well as the inhomogeneities within the sheet profile, a small amount of the laser light sheet intensity can be decoupled by means of a beam splitter (T60 at 226 nm at 45°) into a quartz glass cuvette (reference cell) with a fluorescence substance. The fluorescence signal of the reference cell is then coupled on the camera chip by means of an UV enhanced aluminum mirror (Edmund Optics 1/10 λ, 250-700 nm, $R_{avg} > 85\%$). The reference cell must be positioned in a way allowing for the optical path length from the image plane of the camera to the reference cell to be equal to the path length from the camera to the light sheet in the test chamber.

A band pass filter (3 mm thickness) having the transmission maximum of $> 85\%$ in the range of 320 to 360 nm (UG 5 Schott) ensures that the laser sheet wavelength and thus potential reflections from the nozzle are filtered out and only fluorescence light is visible. In this setup, the ICCD-camera (Imager Pro X,

detected by an appropriate detector (usually, a CCD camera equipped with an image intensifier). From the recorded LIF-signal intensity, instantaneous, spatially resolved information on the local amount concentration of the fluorescing molecule can be inferred.

Compared to other techniques, the signal strengths obtained with LIF can be very high, allowing two-dimensional measurements in planar geometries at good signal-to-noise ratios [11]. Importantly, the LIF-signal can often be discriminated from direct laser light based on its different wavelength. This is especially important in the presence of walls or other condensed-phase objects near the measurement volume, since these often cause scattered laser-light, possibly overlapping the actual signal. With LIF, this undesired overlap can often be prevented very efficiently using appropriate optical filters.

Tracer selection

Since the gases chosen for our free jet experiment do not contain molecules that are capable of easily excitable and strong fluorescence excitation, some fluorescing substance (a tracer) has to be added to the flow. Several such substances exist and have seen wide application in the literature [12].

Requirements for the tracer substance molecule are:

- Sufficiently strong signals with good spectral discrimination from laser-light
- No/little influence of the tracer onto the flow field
- Possibility of quantitative evaluation of signals into mixing field quantities (e.g., mixture fraction)
- Ease of seeding the tracer into gas phase (evaporation issues)
- No interference with LIF-signals of other substances (including those produced in chemical reactions)
- Applicability in reacting, high-temperature flows.

A large number of tracers, (often, oxygenated and/or aromatic hydrocarbons) can fulfill most of these demands to some degree (depending on the particular application) [12] but usually fail to meet the last two criteria. Consequently, these substances have not been used for quantitative investigations of mixing fields in reacting gas jets. In our application, which aims at measuring mixing fields also for the reacting case, strategies based these tracers on are not viable. One tracer candidate is nitric monoxide (NO). Due to its well-known spectroscopic properties, and because it can exist also in high-temperature reacting environments, it lends itself as a tracer molecule for the investigations of gas jets.

NO is a gas at standard conditions, the effort of gas-phase seeding is therefore relatively small, compared to other molecules which are liquids at standard conditions, and are sometimes hard to evaporate in defined amounts. Some drawbacks exist, however, notably the strong weakening of the NO-LIF signal by collisional quenching [12]. This is particularly significant when oxygen is present.

Preliminary experiments have shown that in our setup, NO concentrations of 2000 ppm result in good LIF-signal strengths for cold, oxygen-free conditions.

Conversion of NO signals to mixture fraction

NO is well characterized spectroscopically (as described e.g. in Bessler et al. [13]). The signal strength F_{LIF} emerging from some point within the observation plane depends, in the linear fluorescence regime, linearly on the laser energy I_{Laser} and the local NO-concentration (number density) c_{NO} [14,15] according to

$$F_{\text{LIF}} \propto K I_{\text{Laser}} c_{\text{NO}} \sigma(T, p, X_i) \Phi(T, p, X_i). \quad (1)$$

For a measured LIF signal F_{LIF} and known values K , σ , I_{Laser} and Φ , this can be solved for the concentration of NO. Here, K is an experimental factor, σ is the (state-dependent) effective absorption coefficient and Φ denotes the fluorescence quantum yield, which is also a state-dependent quantity.

For an ideal gas mixture, the mole fraction of NO x_{NO} is related to the NO concentration, temperature T and total pressure p by $x_{\text{NO}} = \frac{[\text{NO}]RT}{p}$ with the universal gas constant R .

For the description of turbulent mixing processes in non-premixed combustion, the molar mixture fraction ζ can be used as a measure of the fractional amount of jet-originating matter in the mixing field of jet and ambient gas. The mixture fraction can be defined on a mass basis or on a molar basis. Here, we use a molar mixture fraction, defined as

$$\zeta = \frac{x_{\text{NO}} - x_{\text{NO}_a}}{x_{\text{NO}_j} - x_{\text{NO}_a}}, \quad (2)$$

where the subscript a in equation 2 refers to the ambience and j refers to the jet [16]. Thus, ζ is a normalized quantity ranging from 0 (surroundings) to 1 (jet, maximum possible amount of NO).

In principle, the way from a measured LIF-intensity field to a mixture fraction field leads over the determination of NO-mole fractions from the LIF-signal via eq. (2). However, one needs to account for several non-idealities which can render this procedure difficult. In the following section, strategies are pointed out which allow for laser energy variations, both absolute from shot-to-shot and vertical sheet profile variations.

Hybrid seeding and self-normalization

A quite straightforward way of dealing with laser energy variations is based on ‘‘background seeding’’, which requires no additional optical components for the fluorescence setup. The method, which can be viewed as a hybrid form of jet-seeding and ‘‘inverse seeding’’ (i.e., seeding of the ambience) is best explained by means of Fig. 2 (left image), which shows a typical LIF image (on a false color scale) from a jet and its surroundings. The image intensity is color coded by a blue-green-yellow-red color scale.

The free jet gas (emerging from the top) is a 4.8% N_2 / 95% He (mol/mol) mixture seeded with 2000 ppm NO. It therefore causes a strong NO-LIF signal. The ambient gas surrounding the jet in the test chamber is nitrogen with by-mixing of small amounts of jet gas. Such a seeding is easily achieved by injecting some free jets into the closed chamber, prior to the actual jet measurement. The jet gas/nitrogen mixture is homogeneous after a few seconds. The fluorescence in the jet and in the ambience close to the jet displays the well-known pattern of horizontal stripes, which stem from laser-sheet intensity fluctuations.

The seeding in both the jet and in the ambience creates a kind of laser-sheet reference, similar to fluorescent dye cells used for laser-sheet correction. The reference with hybrid seeding is, however, internal, and offers some additional benefits, as will be shown below.

The LIF-signal can be corrected for horizontal inhomogeneities, and also be self-calibrated to a mixture-fraction related quantity by the hybrid seeding method. This ‘‘self-normalized’’ quantity F^* is defined by

$$F_{xy}^* = \frac{F_{xy} - F_{xy}^a}{F_{xy}^j - F_{xy}^a}. \quad (3)$$

x and y here refer to the row-wise and column-wise coordinates, respectively, of the images.

F_{xy} is the recorded LIF-signal strength at image location x,y . The image F^a represents the LIF-intensity for pure ambient gas (N_2 seeded with small amounts of jet gas). It is derived from F by:

$$F_{xy}^a = \frac{1}{w} \sum_{y^*=L}^R F_{xy^*} \quad (4)$$

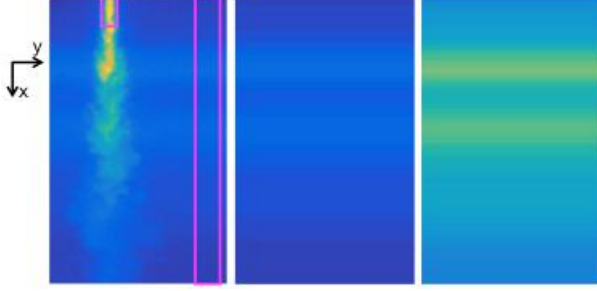


Fig. 2 Left: raw LIF image of a free jet and its ambience in the cell. Pink rectangles indicate position of probe regions for the ambience (right rectangle) and jet gas (small rectangle, drawn here slightly bigger than the actual rectangle used for image evaluation). Center and right: The images F^a and F^j , respectively, derived from the LIF-image. Actually, $0.3 \cdot F^j$ is shown here to bring all images to a comparable color scale. Image size is 37.53 mm by 22.48 mm.

i.e., each row of the image F_{xy}^a contains the average LIF-signal from that row within the ambient sample rectangle. L and R are the left and right boundary columns of the sample rectangle, and w is its width. This rectangle corresponds to a region (ambience) where the mixture fraction is equal to zero. F^a is constant along columns (center).

Likewise, an image representing the LIF-intensity for pure jet gas can be derived from F^a and from information from the jet exit region (corresponding to mixture fraction 1) in the recorded LIF-image. This jet exit region is represented by a small rectangle at the jet exit, extending from row u to row d and column r to column l . Note that in the figure, this rectangle is drawn slightly larger than the actual rectangle, for better graphical representation. The image is then

$$F_{xy}^j = F_{xy}^a \frac{f^j}{f^a} \quad (5)$$

with f^a the average of F within a region from column L to R and row u to d :

$$f^a = \frac{1}{BH} \sum_{y^*=L}^R \sum_{x^*=u}^d F_{x^*y^*} \quad (6)$$

Here, $B=R-l+1$ and $H=d-u+1$.

f^j denotes for the average LIF signal in the probe area in the free jet close to the nozzle.

$$f^j = \frac{1}{bh} \sum_{y^*=l}^r \sum_{x^*=u}^d F_{x^*y^*} \quad (6)$$

with $b=r-l+1$ and $h=H=d-u+1$.

The quantity F^* is related to the mixture fraction; more precisely, inserting the formula for the LIF-signal into the definition of F^* , one obtains:

$$F^* = \frac{(KI_{\text{Laser}}\sigma c_{\text{NO}}\Phi) - (KI_{\text{Laser}}\sigma c_{\text{NO}}\Phi)^a}{(KI_{\text{Laser}}\sigma c_{\text{NO}}\Phi)^j - (KI_{\text{Laser}}\sigma c_{\text{NO}}\Phi)^a} \quad (7)$$

where the superscripts refer to ambient (a) and jet gas (j) conditions, respectively.

In an isothermal constant-pressure flow, the concentration is proportional to mole fraction (by a factor $p/(RT)$); the proportionality factor cancels out in F^* . Assuming that the quantity KI_{Laser} varies only in vertical direction (which is checked easily by recording LIF images in the cell filled with ambient gas only), this simplifies to

$$F^* = \frac{(\sigma x_{\text{NO}}\Phi) - (\sigma x_{\text{NO}}\Phi)^a}{(\sigma x_{\text{NO}}\Phi)^j - (\sigma x_{\text{NO}}\Phi)^a} \quad (8)$$

The quantity F^* can be inferred from the measured fluorescence signal. On the other hand, for given conditions (composition, pressure, temperature) in the ambient gas and in the jet gas, and assuming that all quantities (mole fractions of species) in the mixing field depend only on mixture fraction, the dependence of F^* on the mixture fraction can also be computed theoretically by spectroscopic calculations.

These calculations include the complex dependence of the fluorescence quantum yield Φ on the composition via effects of quenching. Here, spectroscopic data for NO from the literature, especially [17–20] were used.

Figure 3 depicts the calculated F^* as a function of the molar mixture fraction ξ . The inverse of this function (i.e., $\xi(F^*)$) is the key for conversion of the quantity derived from measurements (F^*) to the desired, physical quantity ξ .

The different curves refer to different NO seeding levels in the jet NO_j , as indicated in the legend. The amount NO_a in the ambience correlates with NO_j , since the seeding gas for the ambience is jet gas. The legend shows that, e.g., the theoretically computed strength of the LIF-signal in the jet gas F^j decreases only from $3.4 \cdot 10^{-27}$ to $3.2 \cdot 10^{-27}$ (in arbitrary units) when NO_j is decreased by a factor of 4 from 2000 ppm to 500 ppm.

Therefore, according to the spectroscopic simulations, when doubling the NO-seeding rate of the jet as well as the ambience, the LIF signal F^a and F^j , would not increase by the factor 2 as well. According to the spectroscopic calculations, the seeding rate of 2000 ppm used in this study generates a quite non-linear curve. This may cause a malign error propagation during the conversion from F^* to molar mixture

fraction, especially for mixture fractions close to 1. At lower NO seeding rates, a more linear relation results, allowing a less noise-prone transformation from F^* to mixture fraction.

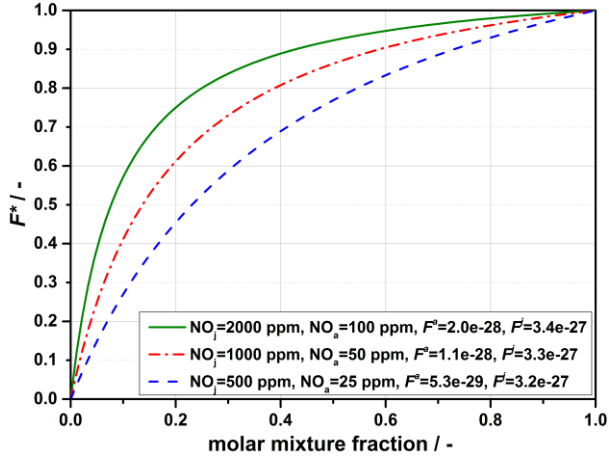


Fig. 3 Computed relation between F^* and molar mixture fraction

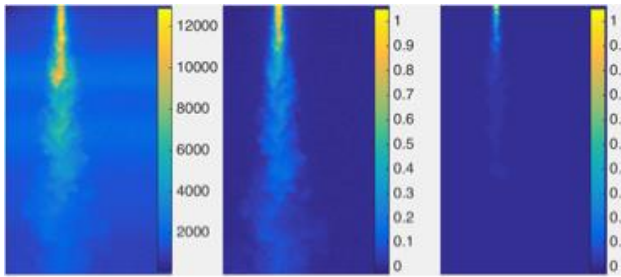


Fig. 4 Stages during conversion from raw LIF image (including laser-sheet variations, left) via F^* (center) to molar mixture fraction (right).

The actual procedure for conversion from measured values of F^* to the molar mixture fraction can be obtained from the curve in Fig. 3 by inverse interpolation. Alternatively, an analytical function can be fitted to the $F^*(\xi)$ curve. By inversion, ξ becomes available as a function of F^* . For our configuration with $\text{NO}_j=2000$ ppm, $\text{NO}_a=100$ ppm, at 1 bar, 300 K, we obtained from a near-perfect fit:

$$\xi = \frac{F^* \cdot a}{(1 - F^* \cdot b)}, \quad (9)$$

with $a = 0.08325$, $b = 0.91675$.

Fig. 4 shows the steps from raw signal to mixture fraction via F^* for one particular example shot of the jet. Note that the resulting mixture fraction field looks different than the field F^* , due to the nonlinear relationship between ξ and F^* .

This “hybrid-seeding” method works well if a reliable homogeneous seeding of the background with NO is possible. However, in presence of oxygen in the ambience, NO will quickly react to form NO_2 at room temperature, impeding the method of background seeding.

Reference Cell

A conventional external reference cell can be used for the reactive case instead of the background seeding. Here, after sheet formation, the laser sheet passes a beam splitter, which decouples around 40 percent of the laser sheet intensity onto a reference cell before entering the test chamber (see figure 1). By means of a mirror, its fluorescence is then coupled onto the same camera as the jet image.

Previous studies conducted by Fast [1] or Sadanandan [6] have applied such a reference cell filled with a dye solution for investigating mixing processes in free jet flows. Here, the fluorescence signal at a known concentration of the tracer molecule cannot be obtained from the reference cell, but is gained from the LIF signal in an area close to the nozzle of a stationary free jet.

When using a reference cell filled with free jet gas (including the seeded NO) instead of a dye, however, this value could be obtained in addition to laser energy and –profile information from the reference cell directly. Furthermore, a possible excitation wavelength shift of the dye laser due to temperature variation can be accounted for. Also, the fluorescence emission wavelength range of the reference and the jet gas tracer would be similar, which can be beneficial if e.g., the employed detectors have a nonlinear detection efficiency over different spectral ranges. LIF-studies using a reference NO cell for calibration and monitoring laser wavelength have been performed by e.g. [21–23].

The clear advantage of this method applies for the reactive case as it does not interfere with the combustion process inside the test chamber. Nevertheless, the adjustment of the dye cell itself and the sheet decoupling optics (beam splitter, mirror) is quite sensitive, thus time consuming and there is a risk of distorting the laser profile during the decoupling process.

Table 1 Overview of the major advantages and disadvantages of external and internal laser energy references.

	Background Seeding	Dye Cell	NO Cell
Experimental simplicity	+	-	-
Spectroscopy jet-reference same	+	-	+
Dynamic range jet-reference same	-	+	+
Applicability to other cases	-	+	+

Table 1 gives an overview of the major advantages and disadvantages of the external and internal references. It can be seen, that the NO cell seems to be a promising solution for the reacting experiments planned

within this project. However, for the non-reacting case, the background seeding seems to be applicable as well. Its clear advantage is the experimental simplicity.

Conclusion

Some experimental strategies for the detailed, quantitative measurement of the mixing field at transient free gas jets by means of laser-induced fluorescence are discussed and compared with respect to the quality of information deferrable, and the practical feasibility. Issues concerning the selection of fluorescent markers, seeding strategy, fluorescence quenching, correction of spatial and temporal variations in the laser-illumination field, and the conversion from raw signals to absolute mixture fraction values are presented. A hybrid seeding method is proposed which affords straightforward self-calibration and laser-sheet correction in LIF-images. These experimental data can be combined with spectroscopical calculations to convert the observed signals to mixture fraction fields.

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