

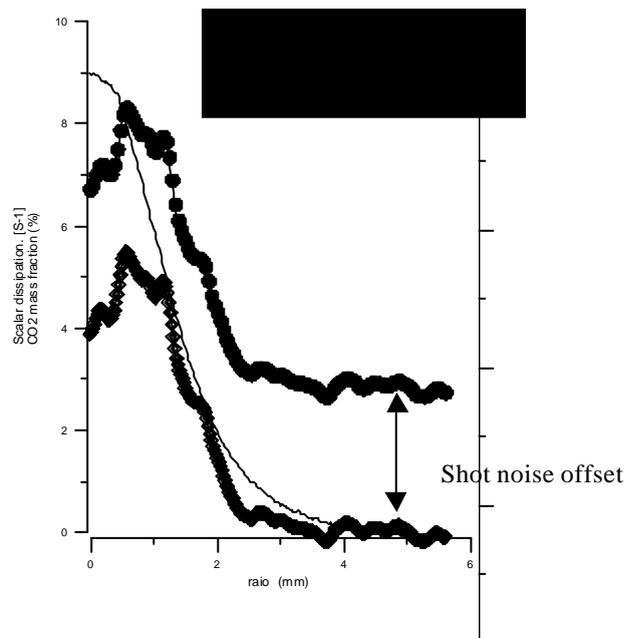
ON THE ACCURACY OF SCALAR DISSIPATION MEASUREMENTS BY LASER RAYLEIGH SCATERING.

P.Ferrão, M.V Heitor and R. Salles
Instituto Superior Técnico
Mechanical Engineering Department
Technical University of Lisbon
PORTUGAL

Abstract

A new sensor for high spatial resolution scalar dissipation measurements is presented together with a dedicated signal analysis, which enables the compensation for systematic uncertainty inherent to the diagnostics technique. The sensor is based in Laser induced Rayleigh Scattering (LRS), from a pulsed laser, in a coaxial CO₂-air jet. The light is collected by a linear array sensor, allowing for instantaneous line measurements of the CO₂ mass fraction. The main sources of uncertainty are the shot noise caused by photon statistics and Mie scattering from particles in the flow. Improvements in signal quality were achieved by increasing laser intensity, carefully designing the acquisition electronics, and developing data processing strategies.

The analysis performed, showed that the shot noise of a LRS measurement induces a systematic error which gives rise to an offset in the dissipation measurements. An expression to evaluate the scalar dissipation offset, as a function of the shot noise variance, was derived. The results obtained are illustrated in the figure below, which represent the effect of the LRS shot noise correction in the raw scalar dissipation measurements obtained.



The negligible scalar dissipation obtained for regions where CO₂ concentration vanishes, contributes to validate the methodology developed and, as a consequence, this experimental technique can be considered as an accurate scalar dissipation diagnostics for complex multi-fluid turbulent shear flows.

Introduction

Despite the extensive use of turbulent flows by today's industry in many different engineering applications, its exact behaviour continues to be poorly understood. The complexity of such flows becomes even more prominent when chemical reactions are involved, like in turbulent flames. Computer simulation is becoming a tool of increasing importance when turbulent flow predictions are required. As this kind of simulation relies entirely on mathematical models, experimental data for physical analysis and validation purposes becomes of great importance.

Among many physical quantities involved in model prediction of turbulent flows, scalar dissipation is one of the most difficult to measure (Namazian et al. (1988); Effelsberg and Peters (1988)). It describes the destruction of the fluctuation of a passive scalar at the finest scale of a given flow (Boyer and Queiroz (1991)). Many assumptions have been made about the character of the scalar dissipation. Elgobashi and Launder (1983) simulated the turbulent thermal dissipation in a flow using the transport equation. Kollman and Janicka (1982) used a quasi-Gaussian model for a scalar dissipation term on reacting flows.

As discussed by Boyer and Queiroz (1991) the available experimental scalar dissipation data is modest, some investigators presented temperature dissipation data in heated air jets (Sreenivasan et al 1977, Antonia et al 1983, Antonia et al 1984, Antonia and Mi, 1993, Anselmet et al 1985). Namazian et al. (1988) obtained concentration dissipation on methane jets using Laser Raman techniques, presenting scalar dissipation and probability density functions for the dissipation values. However, it is clear that quantitative multipoint dissipation values are still rare. Providing an adequate instrument for measuring scalar dissipation constitutes the main motivation for the present work.

The experimental set-up developed is aimed at accurately measuring scalar dissipation on complex multi-fluid shear flows, by simultaneously scanning a large number of scalar measurements over a line, making use of Laser Rayleigh Scattering (LRS). In the present case, it is advantageously applied to CO₂ concentration measurements since it does not disturb the flow, and allow the simultaneous acquisition of data for a large number of points (1024), and this results in high spatial resolution.

The major problem affecting the accuracy of the method derives from the shot noise associated with LRS measurement. Although irrelevant for mean concentration measurements, shot noise will lead to an overestimation of the root mean square (rms) of instantaneous concentration. This leads to an erroneous scalar dissipation measurement, if it is not properly accounted for, and thus, this paper includes the quantification of this systematic error and defines procedures that compensate its influence on the measurements.

A laser based diagnostic system for spatially resolved measurements of scalar dissipation has been developed and experimental methodology for minimising related uncertainties is presented and validated in a coaxial CO₂/air jet for Re=50000.

The paper is organised in six sections including the introduction. The next sections describe the experimental set-up developed and the main flow characteristics. The raw experimental results are presented in section 4, where the main sources of uncertainty are identified. Section 5 develops a strategy to compensate for the systematic errors inherent to LRS measurements and present experimental evidence that validate the approach followed. The last section summarises the main conclusions of the work.

Experimental set-up

The flow rig developed includes 3 concentric stainless steel ducts where CO₂ flows in the inner duct, and is surrounded by two different annular airflows. The inner tube has an inside diameter of $d=2\text{mm}$ and 1211mm in length. The two air jets are generated by a primary annulus which is $D=24\text{mm}$ in diameter, and a secondary annulus of 150mm . The coaxial jet develops downstream of the tip of the inner and the primary annulus, which is 2mm thick and has a total length of 1125mm . Both tubes are taped at 7° degrees over their final length to a knife-edge at the exit.

The external air jet is used to provide well defined boundary conditions, characterised by a low air velocity (0.5m/s), and contributes to minimise the entrainment of external air in the initial developing region. The total length of the outermost 2mm tick tube is 1000mm.

The experimental set-up, illustrated in figure 1, includes a Nd:YAG laser, working at the 2nd harmonic (532nm), with 200mJ pulse energy was used as the illumination source for LRS measurement. A full frame transfer, cooled CCD camera was responsible for Rayleigh signal detection. The laser beam is focused by lenses to the control volume, the beam diameter at the measurement volume should be around 0.05mm. The light collection system and camera unit has a resolution of 24 μ m.

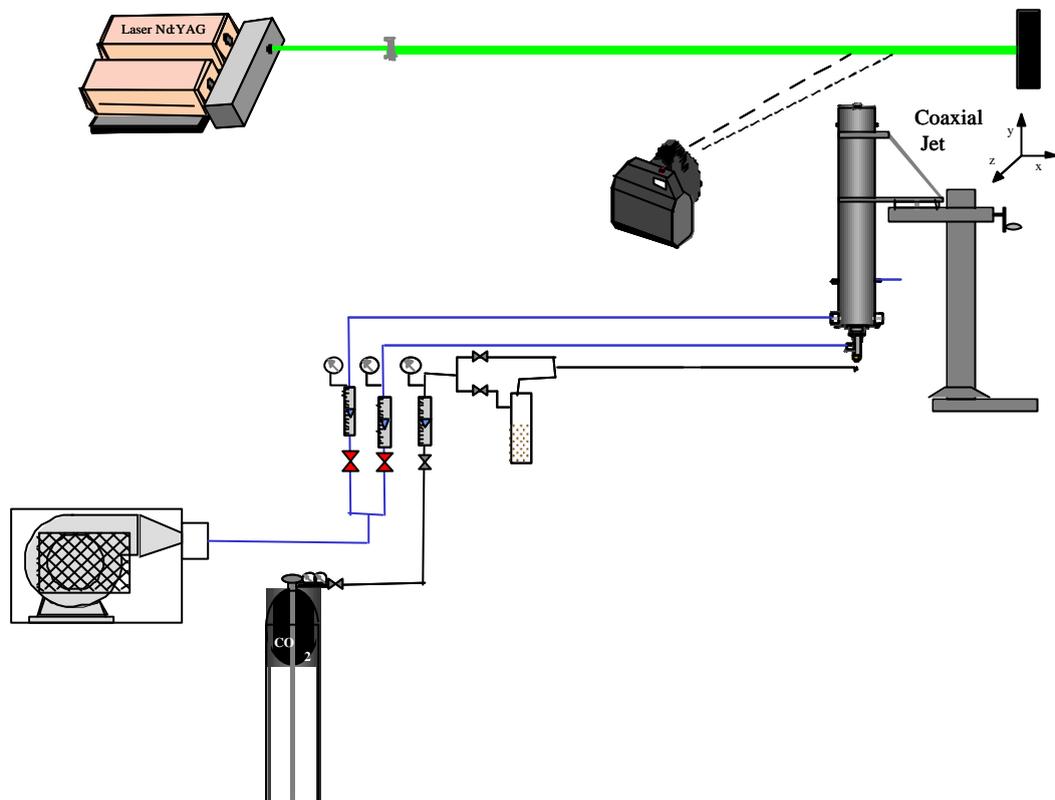


Figure 1 – Experimental set-up

Flow characteristics

The flow analysed is characterised by a CO₂ exit velocity of 55 m/s and a air co-flowing velocity of 33 m/s, and this results in a characteristic Reynolds number of Re=50000.

The characteristic length scales can be associated to the smallest scale of scalar variation, and for a non reacting jet, Dahm and Buch (1991) have suggest that this can be quantified as $11.2xSc^{-1/2}$ times larger than the Kolmogorov scale, η , which is estimated as $\eta=L_0Re^{-3/4}$. The turbulent Reynolds number is defined as $u''L_0/\nu$ where u'' represents the *rms* of the velocity in a given point of the flow, and ν is the kinematic velocity of the fluid. For a free jet, the velocity half radius may be used to approximate L_0 , as discussed by Boyer and Queiroz (1991). Considering this approach, for the conditions of the present experiment, the estimated scalar dissipation micro scale is around 60 μ m, which is quite larger than the spatial resolution of the experimental set-up developed, which was quantified as 24 μ m.

The evolution of the scalar adopted, the CO₂ mass fraction along the flow, as obtained in a previous work, Ferrão et al. (1998), making use of LRS point measurements, is represented in Figure 2b). Figure 2a) shows results obtained using the new experimental set-up with the previous results along the centreline, and the reproducibility of the results is evident.

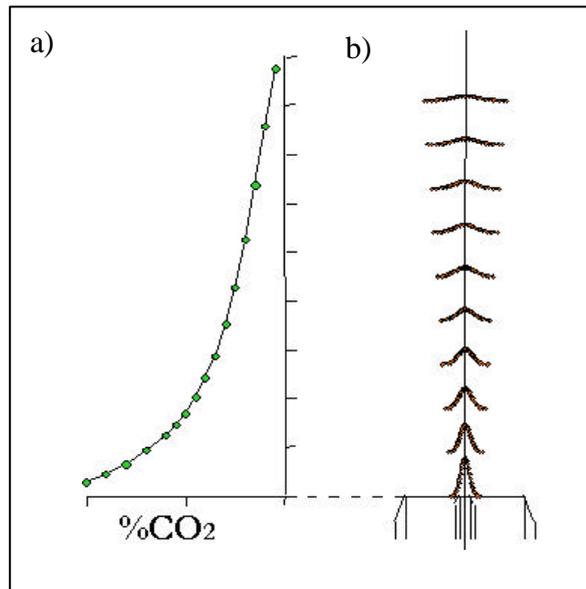


Figure 2 – CO₂ mass fraction; a) along the centreline, measurements obtained by Ferrão et al. (1998) (continuous line) and current measurements (dots) b) radial profiles along the flow by Ferrão et al. (1998)

Experimental results

Laser-induced Rayleigh Scattering (LRS) is the elastic interaction between photons emitted from a laser beam and molecules. Because the scattered energy is proportional to the number density of the measured gas, LRS can be used to measure gas density. At ambient conditions, where pressure and temperature are known, the scattered energy is proportional to the Rayleigh cross section, the incident laser light energy in addition to the gas molecular number density. This technique is thus quite adequate to characterise the mixing of two gases, at the same temperature, as in the present experiment, which includes a co-flowing jet of CO₂ in air. A general procedure adapted to calibrate the measurements is described in Ferrão and Heitor (1999).

The measurements analysed in the next paragraphs, correspond to radial distributions of the CO₂ mass fraction, obtained 20mm downstream the CO₂ jet tip, i.e. for $x/d = 10$. A sample result of the LRS raw signal, for an individual measurement obtained from a single laser shot is represented in figure 3.

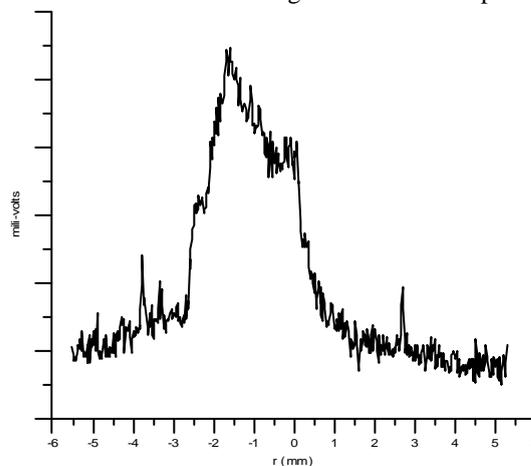


Figure 3 - LRS signal from a single laser shot.

The number of shots required to obtain representative values of the average CO₂ mass fraction for each measurement, was of the order of few hundreds and, to characterise the rms of the CO₂ mass fraction, less than 1000 shots could provide representative data, as illustrated in figure 4. In the experimental analysis that follows, 8,000 shots were performed to characterise each average axial profile, which is thus sufficient to provide a correct characterisation of the turbulent characteristics of the flow analysed.

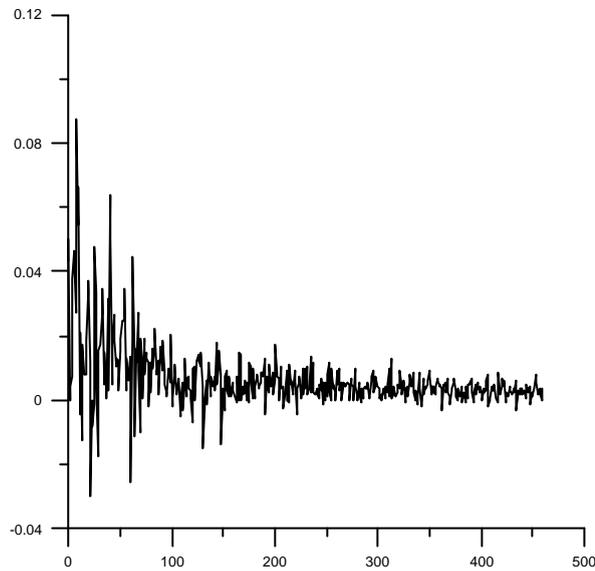


Figure 4: Evolution of the standard deviation of the average CO₂ mass fraction as a function of the number of instantaneous measurements.

The radial profile of the CO₂ mass fraction *rms*, for an axial location of $x/d=0.1$, is shown in figure 5. The maximum of the CO₂ mass fraction *rms* is located near the centreline and there is a decrease as the CO₂ jet vanishes, but it does not tend to zero, as the measurement point gets far from the jet centreline as it would be expected.

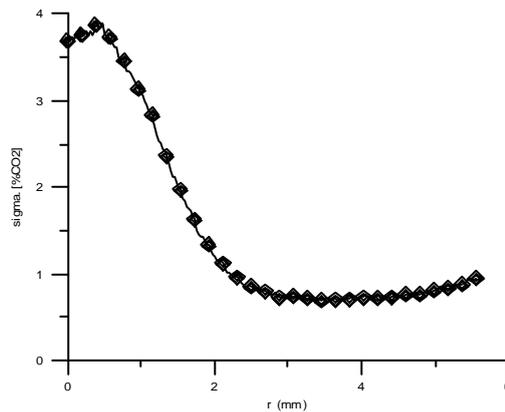


Figure 5: Radial profile of the CO₂ mass fraction *rms*.

Figure 5 clearly identifies a significant rms concentration value for off-axis regions, where CO₂ is no longer available. A particularly severe interference source for LRS measurements consists in the Mie scattered light from small particles present in the flow, as although every measure has been taken to avoid the presence of particles, some are present and interfere with the results. As a consequence, a digital discriminating algorithm has been created to run in real-time during the measurements. An average of the previous 100 shots is compared to each instantaneous measurement and whenever any point of the curve shows a signal more than 3 times higher than the average, the measurement is not recorded.

Taking this into consideration, it may be inferred that the displacement of the rms values of the CO₂ mass fraction should be associated to other sources of uncertainty and, in particular, to the shot noise associated to LRS measurements.

This is particularly significant as the systematic error induced by shot noise is very relevant for the calculation of the scalar (CO₂ mass fraction) dissipation, leading to a dissipation offset, as discussed in the next paragraphs.

Uncertainty associated to scalar dissipation measurements

Considering the scalar representing the CO₂ mass fraction represented by ξ , the component of dissipation in the radial direction, r , can be evaluated by:

$$c = 2D \left(\frac{\partial \mathbf{x}}{\partial r} \right)^2 \quad (1)$$

Where D is the CO₂ diffusion coefficient in air. For the purpose of numerical calculations this equation is approximated by a finite difference of the form:

$$c = 2D(dx)^2 \quad (2)$$

$$dx = \left(\frac{x_2 - x_1}{\Delta} \right) \quad (3)$$

Where ξ_2 and ξ_1 represent the mass fraction at two adjacent points, and Δ is the distance between them.

Considering that the variance associated to the shot noise is σ_ξ^2 and making use of (3), the variance associated to the spatial derivative of the scalar can be given by:

$$s_{dx}^2 = \left(\frac{2s_x^2}{\Delta} \right) \quad (4)$$

And, the mean dissipation can be represented by:

$$\bar{c} = \sum_{i=1}^N \left(\frac{c_i}{N} \right) \quad (5)$$

where N is the number of measurements used for the averaging. If ξ is normally distributed, $d\xi$ will also be, and $d\xi$ can be written as $(\mu_{d\xi} + \sigma_{d\xi}Z)$, where μ represents the average and Z a unitary, gaussian random variable. Substituting this on (5) and simplifying the following expression can be obtained:

$$\bar{c} = 2D \left(m_{dx}^2 + s_{dx}^2 \sum_{i=1}^N \frac{Z_i^2}{N} + 2s_{dx} m_{dx} \sum_{i=1}^N \frac{Z_i}{N} \right) = 2D \left(m_{dx}^2 + s_{dx}^2 \frac{c_{(a,n)}}{N} + 2s_{dx} m_{dx} \frac{Z}{\sqrt{N}} \right) \quad (6)$$

The simplification comes from the fact that the sum of the squares of N unity, normal, random variables result in a qui-square distribution random variable $\chi^2_{(\alpha,n)}$ having N degree of freedom. From (6) it is possible to obtain the following equation:

$$\overline{m_c} = 2D(\overline{m_{dx}^2} + S_{dx}^2) \quad (7)$$

$$\text{VAR}[\overline{c}] = 8D^2 \frac{S_{dx}^2}{N} (S_{dx}^2 + 2\overline{m_{dx}^2}) \quad (8)$$

Where $\overline{m_{dx}^2}$ represents the square of the average of $d\xi$ and S_{dx}^2 , the variance. An important implication of (7) is that the average of the dissipation value will suffer an offset when ξ is subject to shot noise:

$$\text{Shot Noise Offset} = 2D S_{dx}^2 \quad (9)$$

The shot noise offset may be easily evaluated, making use of (9). Here, expression (4) should be used in a flow region where turbulent intensity is negligible, in order for the measured σ_ξ to be exclusively representative of the shot noise variance. In particular, in the current experiments, each acquisition from the CCD delivers 1024 CO₂ concentration measurements, 500 of them in the region of the CO₂ jet profile and the other 524 values describe the Rayleigh scattering of the air coflowing the jet. As the Rayleigh cross-section for air is known, those outside values are advantageously used to estimate the measurement uncertainty (therefore σ_ξ).

Considering the typical values of the present experiment results and using (8) the following results can be obtained:

$$\text{VAR}[\chi] \approx 1 \times 10^{-3} \quad \sigma_\chi \approx 0.1 \text{ s}^{-1} \quad \text{Scalar dissipation offset} = 3.33 \text{ s}^{-1}$$

This value of standard deviation corresponds, for typical value of 4 s^{-1} and a confidence of 95%, to a interval of $\pm 0.2 \text{ s}^{-1}$ (uncertainty around 5%).

The scalar dissipation radial distribution measurements and its correction at $x/d=0.1$, are represented in figure 6. This figure validated the approach developed to correct for the shot noise in scalar dissipation measurements, as for radial locations where CO₂ is no longer available, the corrected scalar dissipation vanishes.

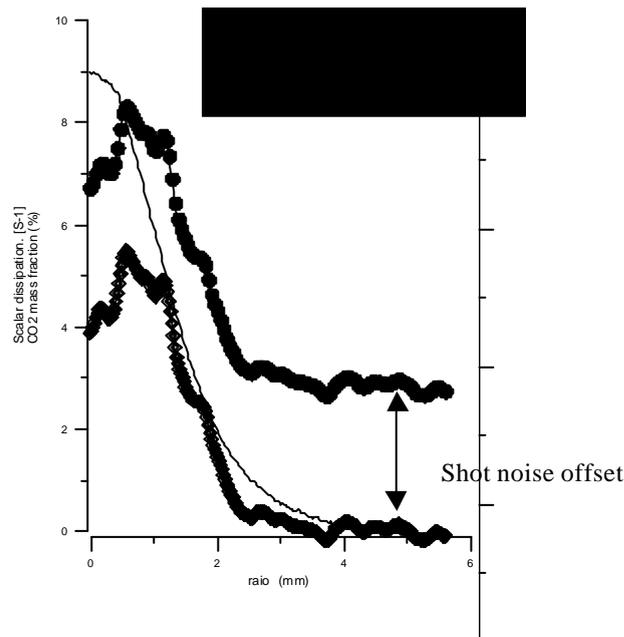


Figure 6: Scalar dissipation for a radial profile located at $x/D=0.1$, and local CO₂ mass fraction.

The systematic error induced by shot noise in scalar dissipation measurements has thus been properly compensated and this confirms the adequacy of the experimental technique developed to measure scalar dissipation with high spatial resolution, despite the shot noise inherent to LRS measurements

Conclusions

A new experimental facility making use of a pulsed laser, to induce Rayleigh scattering in a coaxial CO₂-air turbulent jet, and a linear sensor array to collect the scattered light, were developed for instantaneous linear measurements of the CO₂ mass fraction, providing high spatial resolution scalar (CO₂ mass fraction) dissipation measurements.

Dedicated accuracy analysis was developed to formulate a methodology for compensating the influence of shot noise in scalar dissipation measurements and the results obtained were compared against experimental results. The approach developed was validated and, as a consequence, the experimental technique developed can be considered as an accurate scalar dissipation diagnostics for complex multi-fluid turbulent shear flows.

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