APPLICATION OF 2-COLOR AUTO-COMPENSATING LASER INDUCED INCANDESCENCE IN TURBULENT FLAMES.

M.Bouvier*, J.Yon et F. Grisch
Laboratoire CORIA, INSA de Rouen & Université de Rouen, 76801, Saint Etienne du Rouvray, France
*Courriel de l'orateur : maxime.bouvier@coria.fr

INCANDESCENCE INDUITE PAR LASER AUTO-COMPENSEE A 2 COULEURS EN FLAMMES TURBULENTES.

RESUME
L'Incandescence induite par laser (LII) est une technique optique permettant la mesure in-situ de la fraction de volume de suie. C'est une technique de mesure répandue qui fait encore l'objet de développements. En doublant les dispositifs de détection à deux longueurs d'onde, on peut également déterminer la température d'incandescence des particules, permettant d'améliorer la détermination de la fraction de volume. La méthode d'étalonnage la plus utilisée repose sur une mesure d'extinction de la lumière. Il existe cependant une méthode d'étalonnage dite « auto-compensée » qui permet de s'affranchir de cette mesure d'extinction. Ceci est d'autant plus pratique que, dans certains cas, la teneur en particules ou l'accès optique ne permettent pas une mesure fiable d'extinction. Cependant, on observe que, jusqu'ici, la technique d'auto-compensation associée à une mesure à 2 couleurs n'avait pas été appliquée à des flammes complexes et en particulier turbulentes. Nous présentons ici les premiers résultats de l'application de cette technique en imagerie dans une flamme turbulente dont l'architecture est proche des systèmes de combustion aéronautiques. Une comparaison avec les méthodes classique sera proposée.

ABSTRACT
Laser Induced Incandescence (LII) is an optical technique enabling the in-situ measurement of soot volume fraction. It is a technique which is still subject to developments. By doubling the detection systems at two wavelengths the incandescence temperature of soot particles can be determined, enabling a better determination of the soot volume fraction. The most common calibration method is based on a light extinction measurement. However another calibration method called "auto-compensating" permits to avoid this extinction measurement. This is convenient as, in some cases, the particle concentration or the optical access do not allow any extinction measurements. However we observe that the 2-Color Auto-compensating technique was never applied to complex turbulent flames. We present here the first results of application of this technique in a turbulent flame whose architecture is close to aeronautical combustion systems. A comparison with classical methods will be proposed.

MOTS-CLES : LII, flamme turbulente, soot particles / **KEYWORDS:** LII, turbulent flame, suies

1. INTRODUCTION
Air traffic increase and growing awareness of its climatic impact result in stringent regulation standards to reduce not only gaseous pollutants but also soot emission. In consequence, aircraft motorists have to develop a variety of innovative combustion systems aiming to reduce fuel consumption and soot emissions while maintaining high combustion efficiency. To do this, a detailed understanding of the combustion processes and the ability to numerically simulate the combustion behaviour is mandatory and rely on accurate experimental data. A scientific cooperation between numerous academic research laboratories including the CORIA laboratory and industrial research institutes was recently established to answer those issues for the aeronautic sector (H2020 European program SOPRANO). One of the objectives is to provide accurate data on experimental pilot flames to provide a better understanding about the highly complex soot formation process in high-pressure and high-temperature operating conditions. The current study falls within this project by providing experimental measurements on the SOPRANO burner which is designed to generate reacting flow conditions representative of practical systems, including high turbulence and swirl levels, and which can be operated under premixed and stratified combustion in elevated pressures. Its main objective is to give an accurate understanding of the production of soot particles in such flames. Several operating conditions are investigated including different swirl intensities and different levels of stratification. Flame structure and PAH production were already characterized thanks to OH Planar Laser Induced Fluorescence (OH-PLIF) and PAH-PLIF respectively. Nevertheless, application of the laser induced incandescence (LII) technique in such complex flames is a difficult task due to the intermittency of the soot production and the low levels of soot volume fractions. For these reasons, a specific care has to be taken in order to use and calibrate the optical diagnostic, as it is not classical to perform 2-Color Auto-Compensating LII in turbulent flames (see (De Iuliis, Migliorini et al. 2007) and (Snelling, Smallwood et al. 2005)). The new LII results reported in this study includes soot volume fraction fields for three operating conditions of the burner. These results are very useful in the analysis of the combustion and soot formation processes. Also these results are necessary for the validation of numerical simulations.

2. EXPERIMENTAL SETUP

2.1. Burner design and operating conditions

The base of the burner consists of three concentric tubes in a laminar co-flow, but the central tube is sealed with a ceramic cap, and the flame is stabilized by the recirculation of combustion products downstream of the central bluff body. Two independent fuel/air injection circuits, the inner annulus and the outer annulus ones, are used to inject premixed fuel/air flows at independent equivalence ratios offering the original opportunity to produce a varying stratification ratio for a fixed global equivalence ratio.

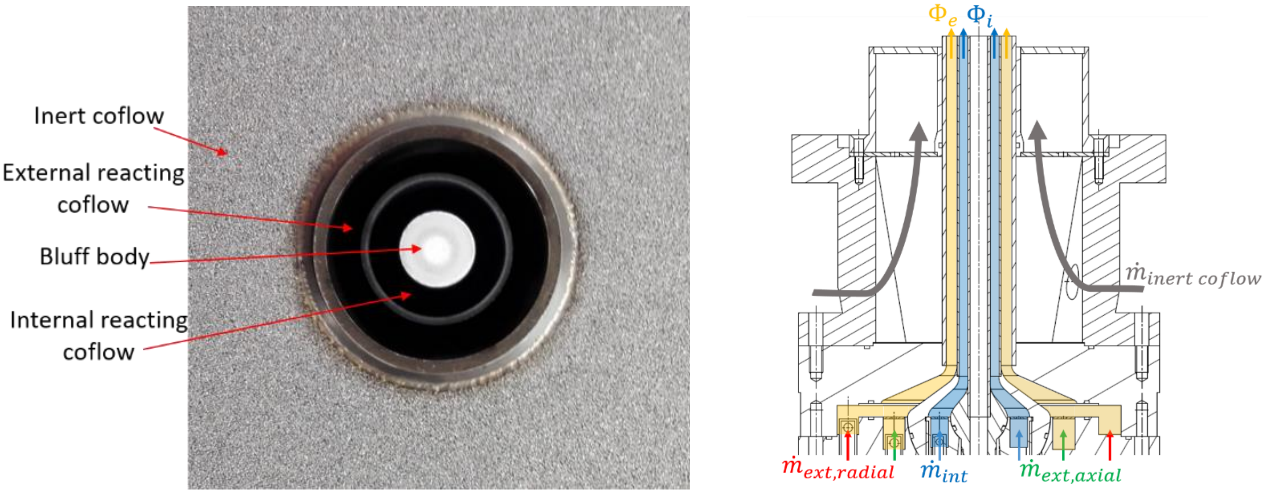

Figure 1 : Exit of the stratified swirl burner (left), plan view of the burner (right).

Figure 1 (right) depicts a cross section of the burner. The operating conditions for the current study are selected to investigate ethylene/air premixed flames in stratified regimes, with varying swirl. The stratification ratio, SR is defined as the ratio of the nominal equivalence ratio in the inner flow (Φ_i) to that in the outer flow (Φ_e).

$$SR = \frac{\Phi_i}{\Phi_e}$$

The swirl, SFR, denotes the ratio of the outer flow rate through the swirl plenum ($\dot{m}_{ext,radial}$) to the total outer annulus flow ($\dot{m}_{ext,axial} + \dot{m}_{ext,radial}$).

$$SFR = \frac{\dot{m}_{ext,radial}}{\dot{m}_{ext,radial} + \dot{m}_{ext,axial}}$$

The operating conditions (total of nine) for the current study have been selected to investigate flames in premixed and stratified regimes, with a varying swirl. Images of the flames recorded for the nine operating conditions are displayed in Figure 2.

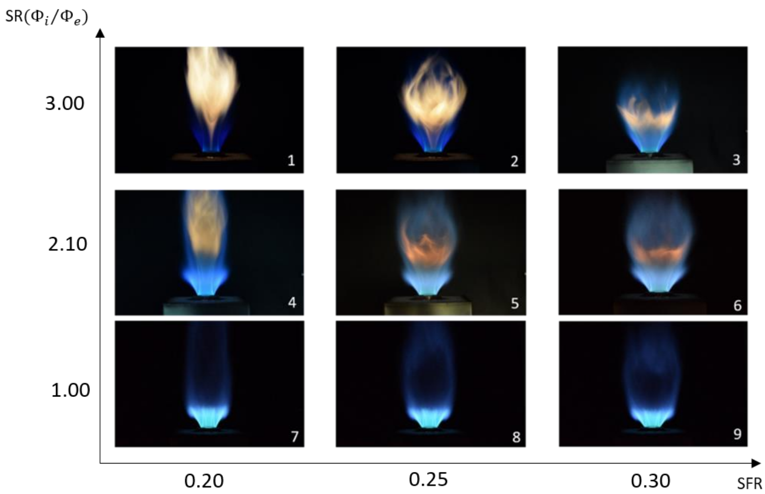

Figure 2 : Photographs of the flame

DOI : 10.25576/ASFERA-CFA2020-19706

2.2. Optical setup

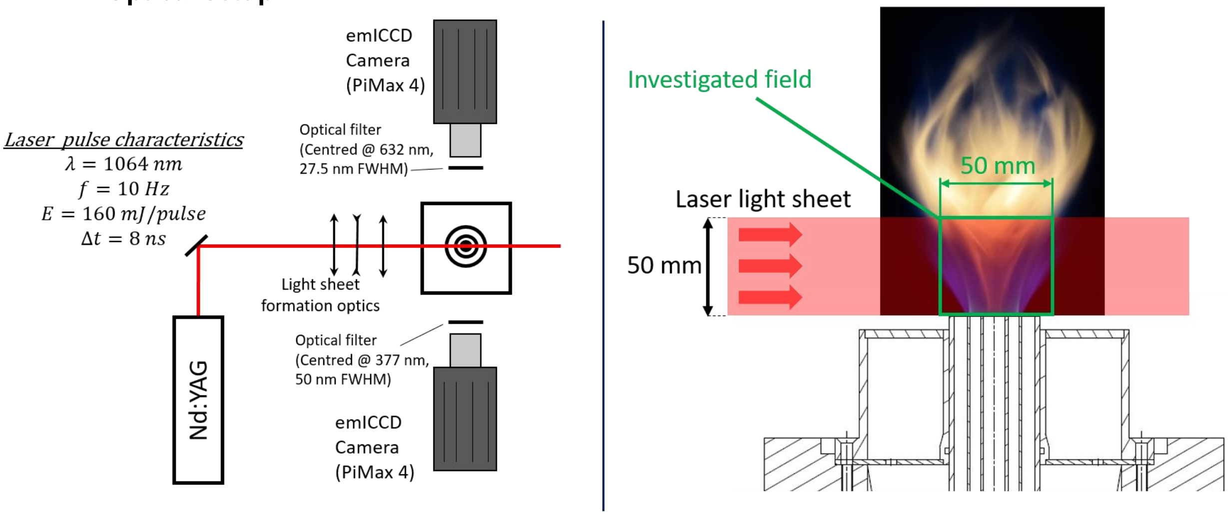

Figure 3 : LII experimental setup

The Figure 3 depicts the experimental setup used for the LII measurements. A 1064 nm laser pulse emitted by a Nd:YAG is transformed into a 50 mm high and 400 µm wide laser sheet which is positioned at the centre of the burner exit. Two emICCD cameras (Princeton instruments PiMax 4) equipped with optical filters (Semrock FF02-632/22 and Edmund Optics #12-096) are positioned perpendicularly to the light path in order to record images of the same field of view (defined by the light sheet).
The calibration step consists in placing an integrating sphere (Labsphere CA-13773-UJF) equipped with a NIST calibrated spectrometer (Labsphere CDS-610) directly in front of the cameras at the exact same place the light sheet is intersecting the flame (see Figure 4). This integrating sphere allows an accurate interpretation of the camera images in terms of radiances.

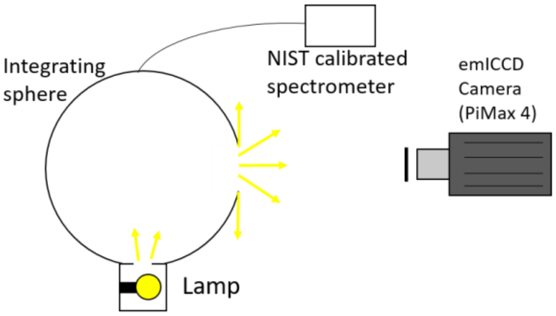

Figure 4 : Calibration setup

3. THEORETICAL BACKGROUND

The radiance emitted by soot particles with a soot volume fraction f_v at the wavelength λ and at the temperature T_s is:

$$L_{s,\lambda}(T_s, f_v) = L_{BB}(T_s, \lambda)\epsilon_s(f_v, \lambda)\Delta\lambda \quad (1)$$

With L_{BB} the black body radiance, ϵ_s the emissivity of the soot and $\Delta\lambda$ a spectral interval thin enough compared to the spectral variation of the flame emission. With Wien approximation for the blackbody radiance and Rayleigh theory to express ϵ_s, the temperature can be derived from the ratio between the soot radiance measured at two wavelength λ_1 and λ_2:

$$T_s = C_2\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\left[ln\left(\frac{L_{s,\lambda 1}}{L_{s,\lambda 2}}\frac{\lambda_1^6}{\lambda_2^6}\frac{E(m(\lambda_2))}{E(m(\lambda_1))}\frac{\Delta\lambda_2}{\Delta\lambda_1}\right)\right]^{-1} \quad (2)$$

with C_2 a known constant, $E(m(\lambda_2))$ and $E(m(\lambda_1))$ the absorption functions at both detection wavelengths which are linked to soot complex refractive index m. The calibration with the integrating sphere enables the quantification of the radiances of the soot particles:

$$L_{s,\lambda} = L_{sphere,\lambda}\frac{I_{s,\lambda}}{I_{sphere,\lambda}} \quad (3)$$

with $I_{s,\lambda}$ and $I_{sphere,\lambda}$ the images measured by the cameras when exposed to the flame and to the integrative sphere respectively. The temperature is then:

DOI : 10.25576/ASFERA-CFA2020-19706

$$T_s = C_2\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)\left[ln\left(\frac{I_{s,\lambda1}}{I_{sphere,\lambda1}}\frac{I_{sphere,\lambda2}}{I_{s,\lambda2}}\frac{\tau_{s2}(\lambda)}{\tau_{s1}(\lambda)}\frac{\lambda_1^6}{\lambda_2^6}\frac{E(m(\lambda_2))}{E(m(\lambda_1))}\frac{\Delta\lambda_2}{\Delta\lambda_1}\right)\right]^{-1} \quad (4)$$

The soot volume fraction is calculated based on the previously determined temperature field and the signal at one of the two detection wavelengths, for instance here λ_2:

$$f_v = \frac{I_{s,\lambda_2}}{I_{sphere,\lambda_2}} L_{sphere,\lambda_2} \frac{\lambda_2^6}{6\pi E(m(\lambda_2))\Delta\lambda_2 L C_1 e^{-C_2/(\lambda_2 T_s)}} \quad (5)$$

with C_1 a known constant and L the laser sheet thickness.

4. RESULTS

The Figure 5 depicts the soot volume fraction measurements obtained by application of the 2-color auto-compensating LII method for three operating conditions, single-shot and time-averaged measurements are reported.

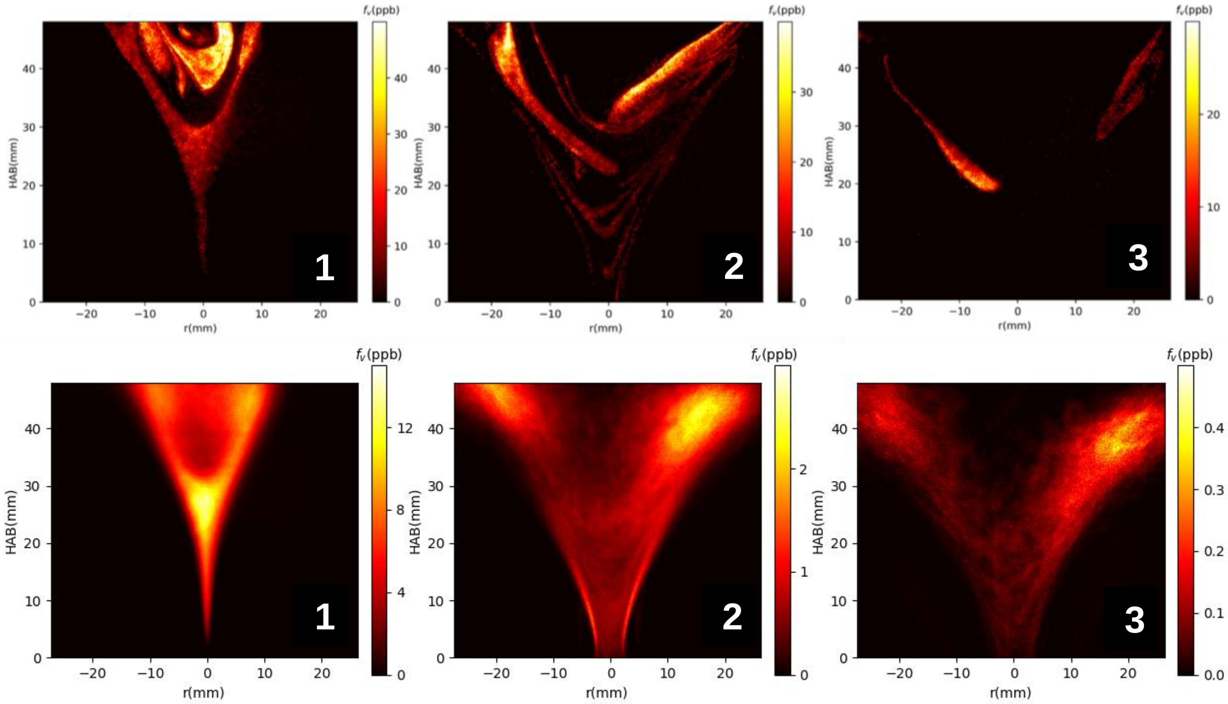

Figure 5 : Soot volume fraction images obtained by LII on the most stratified operating conditions (1,2 and 3), single-shot (top) and time-averaged (bottom).

An inner recirculation zone is produced by the swirling motion and the velocity gradient between the internal and external flow. Large pockets of soot particles can be observed on instantaneous images at the centre of the flames. Stretched filaments are also observed in this central area. As the swirl increases, the probability of capturing a soot pocket is decreasing. The intermittency of the soot signal is very high in the operating condition 3 for instance which leads to very low time-averaged soot volume fraction (0.1-0.4 ppb). This phenomenon is discussed thanks to the calculation of averaged images calculated by taking into account the presence of soot particles (conditioned averages, not presented). It is observed on these conditioned time-averaged images that, when soot particles are detected, their incandescence temperature and volume fraction do not show important spatial and temporal variations.

The comparison of the presently used technique with more classical approaches (extinction based calibration and one wavelength detection) will be presented during the conference.

De Iuliis, S., F. Migliorini, et al. (2007). "2D soot volume fraction imaging in an ethylene diffusion flame by two-color laser-induced incandescence (2C-LII) technique and comparison with results from other optical diagnostics." Proceedings of the Combustion Institute **31**(1): 869-876.

Snelling, D. R., G. J. Smallwood, et al. (2005). "A calibration-independent laser-induced incandescence technique for soot measurement by detecting absolute light intensity." Applied Optics **44**(31): 6773-6785.

DOI : 10.25576/ASFERA-CFA2020-19706