MESURE DE TAILLE DE SUIES DANS UNE FLAMME STRATIFIEE ET SWIRLEE PAR DIFFUSION ANGULAIRE HAUTE CADENCE

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TITLE

Soot size measurement in a swirl stratified flame using high-speed angular light scattering

RESUME

Les travaux présentés dans cette étude concernent des mesures de tailles de particules de suie produites lors de la combustion de l'éthylène. La flamme étudiée est représentative des conditions aéronautiques, c'est-à-dire turbulente, stratifiée (fort gradient spatial de richesse) et swirlée (écoulement rotatif). La diffusion élastique de la lumière est utilisée afin de déterminer la taille des particules de suie. Cette technique est appliquée ici dans un plan à l'aide d'une nappe laser ainsi que de trois caméras disposées à trois angles de diffusion différents. En effet, l'intensité de la lumière diffusée, résultante de l'interaction entre un faisceau laser et l'aérosol, varie en fonction de l'angle auquel on collecte le signal. Cette variation angulaire est une signature de la taille des particules étudiées. Puisque la flamme étudiée est turbulente donc instationnaire, des caméras haute-cadence sont utilisées permettant un suivi dynamique de la taille des particules dans la flamme.

ABSTRACT

The present study concerns size measurement of soot particles which are produced during the combustion of ethylene. The flame which is studied is representative of aeronautic conditions, i.e. turbulent, stratified (high spatial equivalence ratio gradient) and swirled (rotating flow). Elastic light scattering is used in order to determine the soot particle size. This technique is applied in planar configuration thanks to a laser sheet and three cameras placed at three different scattering angles. Indeed, the intensity of the scattered light, which results from the interaction of the laser with the particles, varies with the angle at which the signal is collected. This angular variation allows a determination of the particle size. Because the flame under study is turbulent, high-speed cameras are used in order to enable a temporal tracking of the particles size in the flame.

MOTS-CLES : suies, mesure de taille, diffusion de la lumière, flamme turbulente / **KEYWORDS:** soot, size measurement, elastic light scattering, turbulent flame

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 relies 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 complex soot formation processes in high-pressure and high-temperature operating conditions. The current study falls within this project by providing experimental measurements on the SIRIUS 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. An important parameter in the characterization of the soot particles in flame is the aggregate size. Different ex-situ methods enable its measurement but require a sampling and are not adapted to unsteady flows because they only provide time-averaged data. On the contrary, in-situ optical techniques are suitable for unsteady media and even give the possibility of a dynamic tracking if the laser and detectors operate at a sufficient repetition rate. Elastic light scattering is a technique which permits to measure soot sizes and which was widely investigated and applied in the past in pointwise in flames [1, 2] and more recently in two dimensions in a laminar flame [3]. The present study proposes a development of this technique through an application in a turbulent flow at high repetition rate.

2. THEORETICAL BACKGROUND

A soot particle is an aggregate composed of N_p primary particles with a diameter D_p. These aggregates are considered as fractals, therefore their morphology can be described by the fractal law:

$$N_p = k_f \left(\frac{R_g}{R_p}\right)^{D_f} \quad (1)$$

with R_g the gyration radius of the aggregate, D_f the fractal dimension and k_f the fractal prefactor. The interaction of light and fractal aggregates can be described by the Rayleigh-Debye-Gans theory for Fractal Aggregates (RDG-FA) [4]. This theory adapts the Rayleigh approximation to fractal aggregates using a structure factor (f) which describes the impact of their fractal morphology and size on the scattered light dependence on the scattering angle and wavelength. The vertically polarised radiant power scattered by soot particles contained in a volume V_m under a vertically polarised incident light (irradiance I_0) can be expressed as:

$$I_{vv} = I_0 V_m N_{agg} \overline{\frac{dC_{sca}^a}{d\Omega}}_{vv} \left(f(q, R_g, D_f)\right) \quad (2)$$

with $\overline{\frac{dC_{sca}^a}{d\Omega}}_{vv}$ the forward scattering cross section whose expression is determined by the RDG-FA and N_{agg} the particle number volume concentration, $q = \frac{4\pi}{\lambda} sin(\theta/2)$ and λ the laser wavelength. Defining R the dissymmetry ratio as the ratio of intensities collected at two scattering angles (θ_1 and θ_2) it becomes possible to get rid of many parameters that are unknown or difficult to measure like the primary particle diameter or the complex refractive index:

$$R(\theta_1, \theta_2) = \frac{I_{vv}(\theta_1)}{I_{vv}(\theta_2)} = \frac{f(q_1, R_g, D_f)}{f(q_2, R_g, D_f)} \quad (3)$$

3. EXPERIMENTAL SETUP

The flames studied are produced by the SIRIUS burner. As depicted by the Figure 1, it is composed of purely axial inner flow and an outer flow whose swirl intensity can be monitored thanks to a radial flow injection at the base of the burner (red arrow on Figure 1(b)). A shielding inert gas coflow is injected through a porous media and a bluff body placed in the centre of the inner tube helps the flame stabilisation (Figure 1(a)). Equivalence ratios of inner and outer flows can be controlled thanks to independent mass flow meters.

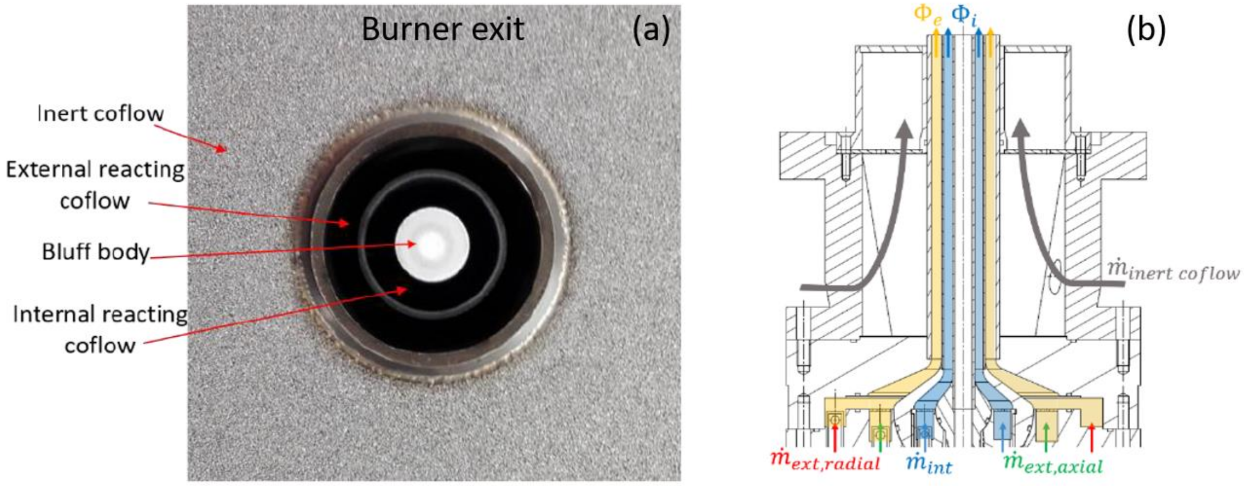

Figure 1 : Top view of the burner exit (a) and plan of the SIRIUS burner (b)

This burner is able to produce various flames from swirled to purely axial, from stratified to non-stratified and from sooting to non-sooting. Different operating conditions were selected in order to characterize the impact of the swirl and stratification on the soot production. The elastic scattering experimental setup is displayed in the Figure 2. Laser pulses produced by a Nd:Yag laser operated at a repetition rate of 1 kHz are attenuated thanks to a half-wave plate and a polarizer and transformed into a sheet of 50 mm high and 100 µm thick. The scattering signal is collected on three cameras placed at diffusion angles of 45°, 90° and 135° with scheimpflug mounts for the camera 1 and 3. Images collected with the camera 1 and 3 have to be dewarped in order to match the images collected by the camera 2. This spatial calibration is performed in two steps : a first one with a target and a second one with the scattering of the laser sheet by micrometric particles in order to be sure that the calibration is performed in the laser sheet plane.

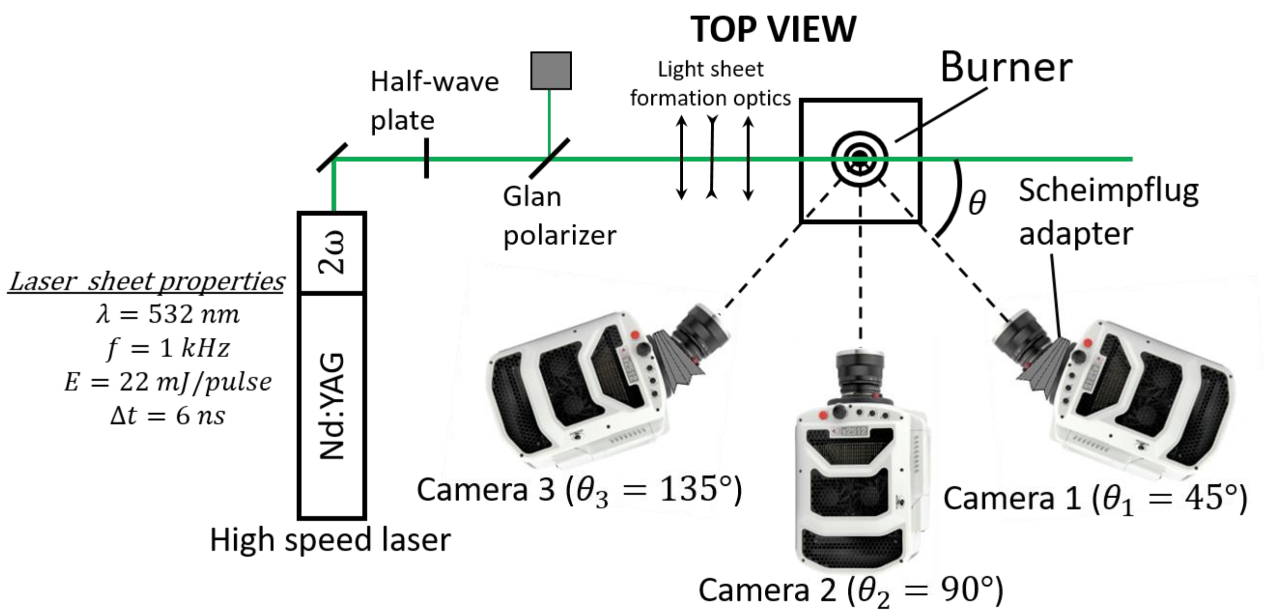

Figure 2 : Optical setup for the 2D high speed angular scattering measurements.

4. RESULTS

Four instantaneous planar gyration diameter fields are depicted in the Figure 3. These fields are calculated thanks to the images collected on the camera 1 and 3, by interpreting $R(\theta_1 = 45°, \theta_2 = 135°)$ Gyration diameters ranging from 15 to 50 nm are observed on these images. Soot are organized as stretched filaments in the bottom of the flame (blue arrow) whereas big pockets are detected higher (green arrow) with no big differences in diameters between these two locations. Spatial variations of sizes are however observed in the big soot pockets especially noticeable on the shot at t = 26 ms with a long filament of large D_g in the left of the pocket. These four shots are taken at different times which are indicated in the bottom left of each 2D field. The large soot pocket pointed by the green arrow can be tracked thanks to the high-speed measurements. It is propagating with a negative vertical velocity because the central area of the flame is actually a recirculation zone, meaning that the flow is going toward the burner exit. This pocket is stretched on its left because of the shear layer of the recirculation zone and eventually end in a long filament in the shot at t = 44 ms.

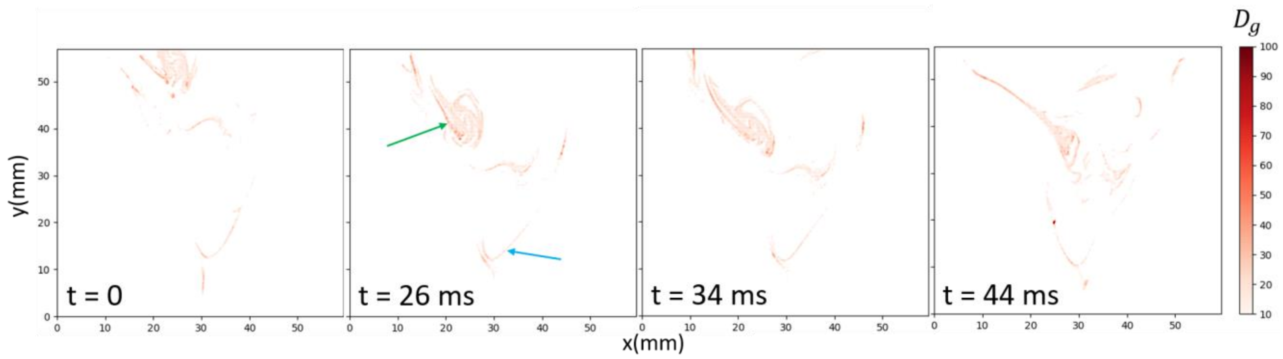

Figure 3 : Gyration diameter D_g two-dimensional fields at four different moments.

After having determined the particles size thanks to the dissymmetry ratio R, it is possible to interpret measurements performed at 90° in terms of particle number volume concentration N_{agg} (using the equation (2)). Without an appropriate calibration, the so determined concentration is not absolute. Nevertheless it enables the observation of the spatial relative dispersion of the particle number density. The field reported in Figure 4 corresponds to N_{agg} at t = 26 ms in the Figure 3. Large variations are observed especially in the soot pockets which appear uncorrelated with the spatial dispersion of the size as reported in Figure 3.

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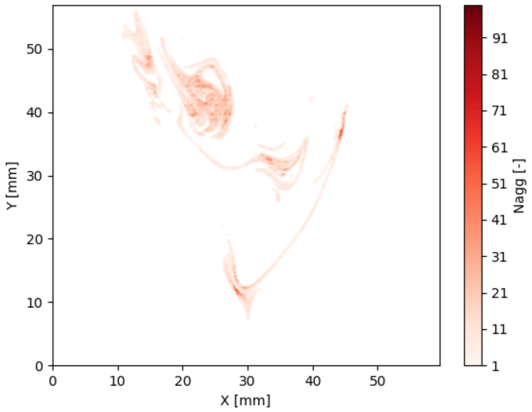

Figure 4 : Particle number volume concentration two-dimensional field.

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