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SOOT SIZING IN LAMINAR DIFFUSION FLAMES : IMPACT OF SELF ABSORPTION

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Abstract

Experimental characterization of soot is recognized as essential for enhancing the understanding of aggregation and oxidation mechanisms occurring directly in flames. Laser Induced Incandescence and Line of Sight Attenuation provide information concerning soot volume fraction but only Angular Light Scattering can inform us of the aggregate size by an in-situ approach. In this work, we aim at improving the spatial resolution and the quality of the size and forward scattering coefficient determination. Indeed, the aggregate size is of interest for the understanding of the formation/oxidation processes whereas the forward scattering contains interesting information on the aggregate volume and optical properties. In particular, we aim at investigating the influence of light self-absorption (or trapping) which is suspected to be the cause of the observed dissymmetry of the scattered signal.

1 Introduction

Soot particles, resulting from the incomplete combustion of fossil fuels, are recognized as the second most significant anthropogenic contributor to global warming [1]. Additionally, their adverse health effects continue to be documented [2]. Although the literature provides information on the soot volume fraction, temperature, and primary sphere diameter [3-5], data on soot aggregates are still scarce, despite their relevance in validating aggregation and oxidation mechanisms. Consequently, the need to provide high spatial resolution data concerning the sizes of soot aggregates emerges as a crucial research question.

In the quest to characterize soot particles, significant efforts have been made to develop in-situ optical techniques. For instance, recent advancements allow the determination of soot volume fraction, temperature, and maturity through multiwavelength line-of-sight attenuation (MW-LOSA) and Emission [6]. The characterization of the aggregate size, number and diameter of primary spheres as well as number density has been recently achieved with a high spatial resolution thanks to the coupling of MW-LOSA and Horizontal Planar Angular Light Scattering (HPALS) [7].

Such optical techniques lead to inversion problems where a specific radial property of soot in axisymmetric flames needs to be reconstructed from the projection that is captured by the optical detection (Abel transform). A critical consideration in this inversion process is the correction for a phenomenon known as signal trapping. Indeed, soot particles can scatter and absorb light. Therefore, as photons travel from their source, pass through the flame, and reach the detector, they experience attenuation along the line of sight. There have been several attempts to correct this effect for emission measurements which is often used to determine the soot temperature [8-9]. However, to the best of the authors' knowledge, this effect has never been considered for angular light scattering measurements.

In the current study, extinction and angular light scattering measurements at a wavelength of 520 nm are presented. A significant signal trapping effect, indicated by pronounced dissymmetry of the scattered profile, is observed in these measurements. To address this, a methodology employing extinction reconstructions is introduced for an accurate reconstruction of the radial property associated with the scattering. We finally evaluate the impact of trapping on the size determination as well as for the determination of the forward scattering coefficient.

2 Methodology

2.1 Experimental Setup

The current investigation examines an axisymmetric laminar ethylene-air diffusion co-flow flame using a Gülder-type burner operating at atmospheric pressure. The burner comprises a 10.9 mm inner diameter central tube for fuel injection and a 90 mm inner diameter co-annular tube for co-flow air supply. To maintain consistent flow rates, two mass flow controllers were employed to supply pure ethylene at 0.194 slpm and air at 150 slpm.

In order to capture images of extinction and angular and spectral scattering of the flame, an experimental campaign was conducted using the device illustrated in Figure 1. A continuous laser source (CELESTA) is operated at 520 nm. The light is collimated with the aid of an achromatic lens ($f = 300$ mm) positioned between the light source and the flame. For LOSA measurements (extinction) and angular

scattering measurements, the light is filtered and captured with a CCD camera (Thorlabs) with an objective lens (Canon 200 mm). The LOSA measurements were performed in-line (0°), while the scattering measurements were taken at 110.2° .

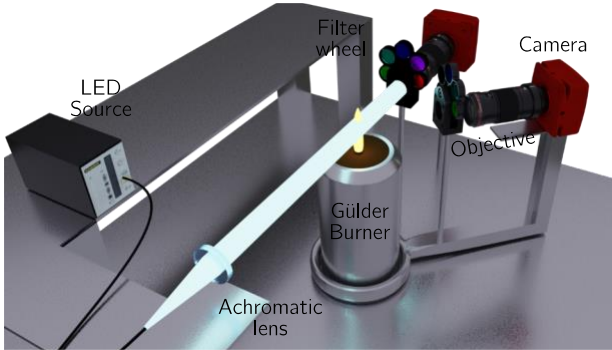


Figure 1 Experimental setup used for extinction, emission and light scattering measurements

2.2 Signal inversion considering self-absorption

Soot particles possess the capability to scatter and absorb light. As a result, when photons travel toward the detector, their intensity is reduced along the line of sight (LoS), a phenomenon known as signal trapping. Therefore, the Abel transform of the measured profiles must be corrected from this effect:

$$P_{sca}(x_s) = 2 \int_x^\infty \frac{K_{sca}(r)F(x_s, r)r}{\sqrt{r^2 - x^2}} dr \quad (1)$$

In this equation, $P_{sca}(x_s)$ is the collected profile on the detector at position x_s , $K_{sca}(r)$ is the researched radial scattering coefficient and $F(x, r)$ is the trapping correction factor introduced in this work.

This factor is evaluated by considering the local extinction coefficient κ_{ext} retrieved from LOSA measurements at same wavelength as well as the trapping occurring from the light source to the particles at a given position D in the flame (green line in Figure 2) and from the particles to the detector (cyan line in the figure):

$$F(x_s, y_s) = \exp \left[- \left(\int_{-\infty}^D \kappa_{ext}(r) dl + \int_D^\infty \kappa_{ext}(r) dy \right) \right] \quad (2)$$

Figure 2-a represents a top view of the flame at a chosen height above burner (HAB); the colours are representative of the degree of attenuation (F) for each position in the flame. The brighter corresponds to stronger trapping. The effect of the trapping consideration is then modelled in the direct way by application of equation 1 to synthetic signals (Figure 2-b). The blue dashed curve is the Abel transform without trapping correction whereas the orange curve considers this effect. We clearly observe the dissymmetry induced by the trapping on the collected signal. We will now apply this model in the opposite way in order to determine the scattering coefficient profile $K_{sca}(r)$ by

inverting P_{sca} . In order to reduce the noise propagation during this inversion process, a novel piecewise Spline-based Abel Transform (SAT) technique is adopted (not presented here). Therefore, the radial profile of $K_{sca}(r)$ made of pieces of spline functions is adapted in order to make its Abel transform (P_{sca}) matching the measurement.

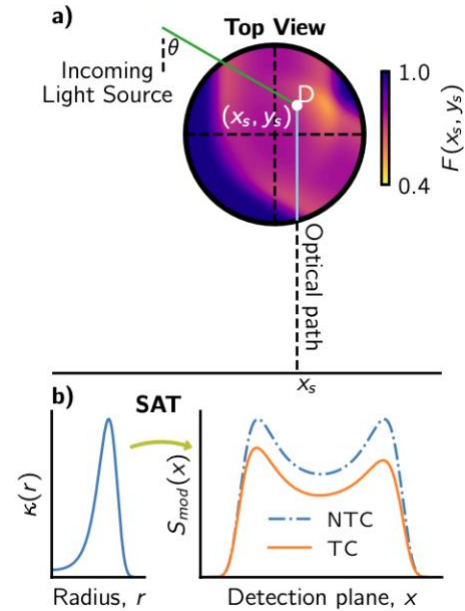


Figure 2 a) Schematic of angular light scattering signal trapping effect. b) Graphic representation of the Spline-based Abel Transform (SAT) method. Starting from a known profile, SAT is applied in the direct way and the modelled measured profile is obtained. It is also shown how the signal is attenuated in the presence of trapping, emphasizing the changes in signal behaviour. The notations TC and NTC indicates when trapping is corrected or not, respectively.

3 Results

Figure 3 reports the measured profile in blue obtained at 30 mm height above the burner and for the scattering angle of 110° and the result of the fitting process by considering (TC) or not (NTC, $F = 1$) the self-absorption.

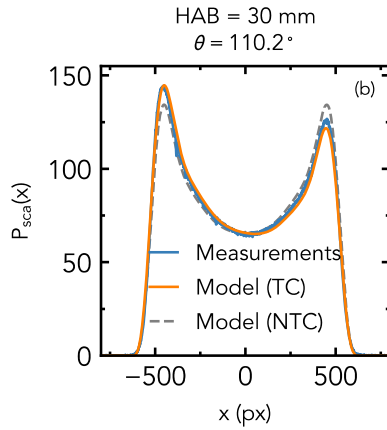


Figure 3 Measured and modelled scattering signals considering (TC) or not (NTC) the trapping of the light.

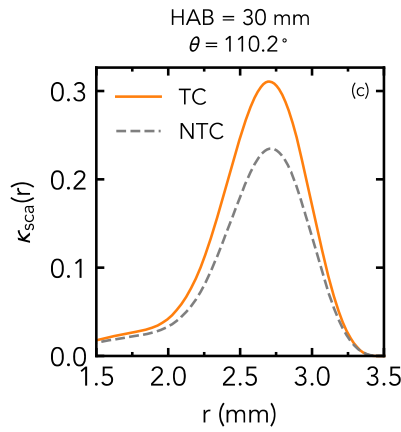


Figure 4 Result of the Abel inversion by considering (TC) or not (NTC) the trapping of the light.

The model enables a good capture of the observed dissymmetry. The corresponding radial profiles of scattering coefficient are reported in Figure 4 by considering or not the trapping correction. We clearly observe, for this flame, wavelength and specific height above the burner a strong influence of the trapping correction, especially in terms of signal amplitude near the wings of the flame.

This operation is then repeated for different scattering angles. We report in Figure 5 the angular profiles obtained at two radial positions respectively $r = 2.1$ and 2.8 mm.

The angular dependence is fitted by an exponential decrease corresponding to a Guinier regime providing the monodisperse equivalent gyration radius R_g^* and the forward scattering coefficient $k_{vv}(0^\circ)$. We observe that R_g^* is not affected strongly by trapping. In turns, the forward scattering is strongly impacted in soot-laden areas of the flame.

4 Conclusion

In this study, a model has been developed for correcting signal trapping in angular light scattering measurements of soot, conducted in a laminar co-flow diffusion flame using a Gülder burner. A significant dissymmetry in scattering profiles, indicative of a pronounced signal trapping effect, has been observed experimentally and well captured by the proposed model. It is found that when signal trapping is neglected, there is an underestimation reaching 40% in the maximum value for the studied case. Therefore, the inclusion of this correction when performing light scattering measurements is recommended even if the repercussion on the soot size determination is shown to be small.

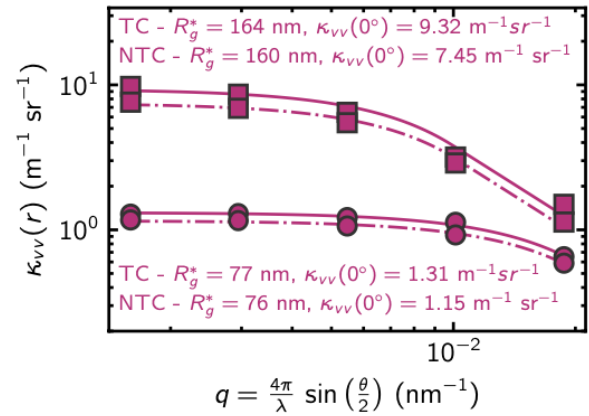


Figure 5 Impact of the trapping correction on the angular scattering dependence and corresponding extracted parameters (gyration radius and forward scattering coefficient).

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