Combustion and Flame 162 (2015) 2705–2719

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Simultaneous soot temperature and volume fraction measurements in axis-symmetric flames by a two-dimensional modulated absorption/emission technique

Guillaume Legros [a,b,*], Qianlong Wang [a,b], Jérôme Bonnety [a,b], Muhammad Kashif [a,b,c], Céline Morin [d], Jean-Louis Consalvi [e], Fengshan Liu [f]

[a] Sorbonne Universités, UPMC Univ Paris 06, UMR 7190, Inst Jean Le Rond d'Alembert, F-75005, Paris, France
[b] CNRS, UMR 7190, Inst Jean Le Rond d'Alembert, F-75005, Paris, France
[c] University of Central Punjab, Department of Mechanical Engineering, Faculty of Engineering, Johar Town, Lahore, Pakistan
[d] LAMIH CNRS UMR 8201, UVHC, F-59313 Valenciennes, France
[e] Aix-Marseille Université, IUSTI/UMR CNRS 7343, F-13453 Marseille Cedex 13, France
[f] Measurement Science and Standards, National Research Council of Canada, Ottawa, Ontario, Canada

ARTICLE INFO

Article history:
Received 7 April 2015
Received in revised form 7 April 2015
Accepted 8 April 2015
Available online 23 April 2015

Keywords:
Soot diagnostics
Flame emissions
Soot volume fraction
Soot temperature

ABSTRACT

The original contribution of the present paper is to present a joint theoretical and experimental approach to implement the modulated absorption/emission technique. Two-dimensional fields of soot temperature and volume fraction can then be measured simultaneously in a reference steady laminar coflow axis-symmetric non-premixed ethylene flame established over the Santoro burner. The spontaneous flame emission is captured by two CMOS cameras that allow the measurements of the flame emission intensity at two different wavelengths, i.e., 645 nm and 785 nm in this study. Concomitantly, two 70 mm diameter laser beams are used to pass through the flame, enabling the spectral line-of-sight attenuation to be imaged at the two wavelengths by the CMOS sensors. In these spectral ranges, both absorption and emission phenomena are dominated by soot. The local spectral absorption coefficient and spectral emission rate at both wavelengths are obtained by the onion-peeling method with Tikhonov regularization. The soot volume fraction map is inferred from the spectral absorption coefficient field. Mapping soot temperature does not require any model correlating soot volume fraction and local spectral absorption coefficient. Only the measurements of the latter at both wavelengths are required to enable the self-calibration of the technique and infer soot temperature from the ratio of the local spectral emission rates. Thus, the issue of the large discrepancies in the wavelength-dependent soot refractive index reported in the literature does not arise. Within the region of high soot temperatures, the results obtained by the methodology are in good agreement with numerical and experimental data available in the literature. The use of continuous wave lasers as the light sources enables future investigations in flickering flames where the phenomenon of intermittent soot release through the flame tip still needs to be better understood.

1. Introduction

Formed along combustion processes, soot particles can be ultimately released into the atmosphere. The presence of these particles in urban air poses a serious public health problem even at low concentration [1]. Recent studies also highlight the critical role that soot particles may play in global warming due to their significant ability to absorb the incoming solar radiation [2]. Therefore, strategies aiming at the reduction of soot release by combustion devices are required.

Soot production is the result of two competitive processes, formation and oxidation. In the last four to five decades, models of both processes have been extensively developed. Some numerical models are capable of producing fair predictions of local soot concentrations [3–8]. However, the accuracy of these models seems to

* Corresponding author at: Sorbonne Universités, UPMC Univ Paris 06, UMR 7190, Inst Jean Le Rond d'Alembert, F-75005, Paris, France.
E-mail addresses: guillaume.legros@dalembert.upmc.fr (G. Legros), wangqianlong212@gmail.com (Q. Wang), jerome.bonnety@upmc.fr (J. Bonnety), muhammad.kashif@ucp.edu.pk (M. Kashif), celine.morin@univ-valenciennes.fr (C. Morin), jean-louis.consalvi@univ-amu.fr (J.-L. Consalvi), Fengshan.Liu@nrc-cnrc.gc.ca (F. Liu).

http://dx.doi.org/10.1016/j.combustflame.2015.04.006
0010-2180/

be strongly flame configuration dependent. While a highly comprehensive numerical approach by Blanquart and Pitsch [7] has been validated over a relatively wide range of fundamental laboratory flame configurations, the methodology requires a large database from each configuration studied.

The results obtained by Blanquart and Pitsch were essentially in good agreement with experimental measurements of soot volume fraction in several laminar flames. The joint Volume-Surface-Hydrogen model developed by the authors for soot formation was shown to predict the bell-shaped curve, i.e., the peak soot volume fraction in the flame first increases with increasing T_{10} (the temperature at 10 mm above the burner) up to a threshold temperature and then decreases as T_{10} is further increased. Still, as highlighted by these authors, T_{10} remains an arbitrary key parameter of the simulations.

In a numerical study conducted on ethylene diffusion flames, Liu et al. [8] extended their CFD code that incorporates both simplified soot chemistry and radiative transfer models. These authors needed to introduce two temperature-dependent correction factors in the soot oxidation schemes to successfully simulate the Smoke-Point for a given experimental configuration, i.e., the conditions that lead to the quenching of the soot oxidation process, therefore to soot release through the flame tip. These authors indicate that the exact physical and chemical processes associated with the modified soot oxidation rates are not fully understood and no guarantees are given that the model will be accurate in other configurations.

Recently, McEnally and Pfefferle [9] investigated potential methodologies to improve the Smoke-Point measurement. These authors assessed the relevance of the Yield Sooting Index (YSI) that quantifies the propensity of the fuel investigated to produce soot. YSI is inferred from direct measurements of peak soot volume fraction in a reference axis-symmetric diffusion flame. Kashif et al. [10] extended the consistency of the YSI methodology to blends of liquid fuels. While these authors reported some full soot volume fraction fields measured in the reference flame to extract the YSI [11], a recent numerical study by Consalvi et al. [12] showed that experimental soot temperature field is required to validate and improve the simulation, and to better understand the YSI methodology.

Thus, mapping soot temperature in these reference flames would allow further validation of sophisticated models of soot formation and oxidation. A considerable number of experimental studies have devoted efforts to the development of optical techniques to measure temperature in sooting flames. Indeed, such non-invasive diagnostics enable the reacting flows to be both probed without any perturbation and mapped potentially over a quite large area. Recent investigations [13–15] showed that the decay signal provided by Laser Induced Incandescence (LII) can give access to the temperature of laser heated soot particles. Nonetheless, the use of two-color or spectrally resolved LII to infer the soot temperature during or after laser heating requires a careful characterization of the wavelength dependence of the soot emissivity [15]. Furthermore, Goulay et al. [15] mentioned that some physico-chemical processes are likely to occur at the surface of the soot during the laser heating, leading to large uncertainties in the evaluation of the actual soot temperature.

As an alternative, the multicolor pyrometry imaging of flame spontaneous emission is also widely applied to both laboratory flames [16–20] and practical devices [21,22]. Based on flame emissions detected by a spectrometer in steady laminar sooting axis-symmetric coflow diffusion flames, Liu et al. [19] extended the pyrometry methodology to multi-wavelength local measurements to reconstruct the soot temperature and volume fraction fields. On a similar flame configuration, Zhao et al. [20] developed the Cone Beam Tomographic Three Colour Spectrometry using a CMOS color camera. This technique allows the green, blue, and red intensities emitted by the soot particles to be discriminated. Maps of soot temperature, volume fraction and mean particle diameter can then be obtained. These techniques require sophisticated data processing as the raw information captured especially depends on both blackbody emission and emissivity, i.e., temperature and soot volume fraction, respectively. The influence of soot self-absorption on the soot volume fraction and temperature retrieval also requires a careful correction for flames exhibiting a relatively high optical thickness. Moreover, the determination of soot temperature depends on the spectral dependence of the soot refractive index, a quantity that is a topic of ongoing debate as large discrepancies are reported in the literature [15,19,20].

To circumvent this issue, Jenkins and Hanson [23] developed the modulated absorption/emission (MAE) technique to probe a steady rich premixed ethylene/air flame established over a McKenna burner. In their experiments in this one-dimensional flame, a photomultiplier was used to detect both the flame spontaneous emission and the absorption of two laser beams through the flame at each laser operating wavelength, i.e., 830 nm and 1300 nm. In this way, the local spectral soot absorption coefficients are directly evaluated at both wavelengths from the laser absorption measurements then used to infer the soot temperature from the ratio of the local spectral emission rates captured at these wavelengths. Using Mie theory in the Rayleigh limit, the spectral absorption coefficient can be converted to the local soot volume fraction with the help of a soot refractive index model. As highlighted by Jenkins and Hanson, the MAE technique provides self-calibrated temperature measurements, i.e., it is independent of the soot refractive index selected.

However, extension of the MAE technique to two-dimensional fields has not been reported in the literature. The main contribution of the present paper is the development of the MAE technique allowing the simultaneous measurements of soot temperature and volume fraction distribution in a steady laminar axis-symmetric non-premixed ethylene flame. To this end, the theoretical methodology that inherently accounts for the soot self-absorption is first described. The numerical distributions of soot temperature and volume fraction provided by Blacha et al. [24] are used to compute the theoretical flame emission signals captured by a matrix of pixels of a camera. Doing so, the relevance of the extended MAE technique and its limitations can be addressed through comparing the numerical fields with the retrieved ones. The experimental setup designed to implement the MAE technique is then outlined. By conducting MAE measurements in the flame established over the Santoro's coflow burner that was simulated by Blacha et al., we finally show that the experimental profiles of soot temperature and volume fraction obtained by the MAE technique agree fairly well with the data available in the literature. The self-calibration of soot temperature can also be used to infer soot temperature maps from the one-color fields of local spectral emission rate.

2. Theoretical methodology

2.1. Geometrical configuration

The methodology is designed for an axis-symmetric configuration. In the following, (Oz) is the flame's axis of symmetry. Its origin is located at the burner tip, defining the height above the burner (HAB). r is the distance from the axis of symmetry. Figure 1 displays a schematic of a flame's cross-section at a given z. For symmetry reason, the quantities, such as the temperature T and the spectral absorption coefficient κ, depend on the cylindrical coordinates r and z, but not on the angular position θ. Defining the cartesian coordinates, the x-axis is set parallel to the sensor S_1 and the y-axis is normal to S_1.