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Simultaneous measurements of gas temperature, soot volume fraction and primary particle diameter in a sooting lifted turbulent ethylene/air non-premixed flame

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ABSTRACT

Simultaneous, planar measurements of flame temperature (T), soot volume fraction (f_v), primary particle diameter (d_p) and the derived number density of primary particles (N_p) are reported in a well characterized, lifted ethylene jet diffusion flame, both to increase confidence in measurement accuracy and to provide new joint statistics. Planar measurements of temperature were performed using non-linear excitation regime two-line atomic fluorescence (nTLAF) of indium with an improved optical arrangement over those reported previously, and were found to yield good agreement with previous measurements obtained with coherent anti-Stokes Raman spectroscopy (CARS). Planar measurements of soot volume fraction and primary particle diameter were performed using time-resolved laser-induced incandescence (TiRe-LII). On the flame centreline, both the measured values of d_p and f_v grow with axial distance to peak near to the mid height of the flame. The joint probability density functions (PDF) of the measured T, f_v, d_p and derived N_p were obtained from the two-dimensional images and assessed at 15 locations in the flame (5 radial × 3 axial locations). Strong correlations were found between f_v, d_p and N_p, while they exhibit a moderate correlation with flame temperature. The changes in PDFs with radial and axial locations and the most probable values are also reported.

1. Introduction

Reliable measurements of well characterised turbulent sooting flames are needed to support the development and validation of predictive models, which in turn are needed to mitigate soot emissions from practical combustion systems that cause deleterious effects on human health and climate change [1–3]. It is also highly desirable that such measurements not only be well resolved spatially and temporally, but also record multiple parameters simultaneously and in multiple dimensions, due to the complex coupling between soot, turbulence, radiation and chemistry. Of these, four parameters of particular interest for modelling soot evolution are soot volume fraction (f_v), primary particle diameter (d_p), number density of primary soot particle (N_p) and flame temperature (T), which influence radiative heat transfer in turbulent flames. However, measurements of these key parameters are rare. Previous studies reported measurements of planar f_v and laser-induced fluorescence (LIF) of polycyclic aromatic hydrocarbons (PAHs) [4], of simultaneous f_v and qualitative hydroxyl radical (OH) concentrations [5] and of simultaneous f_v and velocity [6]. Only a few simultaneous measurements have been reported of T and f_v in turbulent jet flames [7–10] and in pool fires [11,12] and of f_v, d_p and N_p in turbulent flames [13–15]. However, none of these are well resolved both spatially and temporally and of known absolute accuracy, which is desirable for model validation. There is therefore a need for new, more accurate and comprehensive data in a well-characterised flame.

A vital aspect of determining absolute measurement accuracy is the need for independent measurements of identical and well characterized flames with different methods. However, to date, such independent assessments in turbulent sooting flames are rare, due the challenges of performing measurement of key parameters in these environments [16]. For this reason, such measurements are yet to be performed for T, f_v, d_p and N_p. While data are available for several target turbulent sooting flames [17–21],

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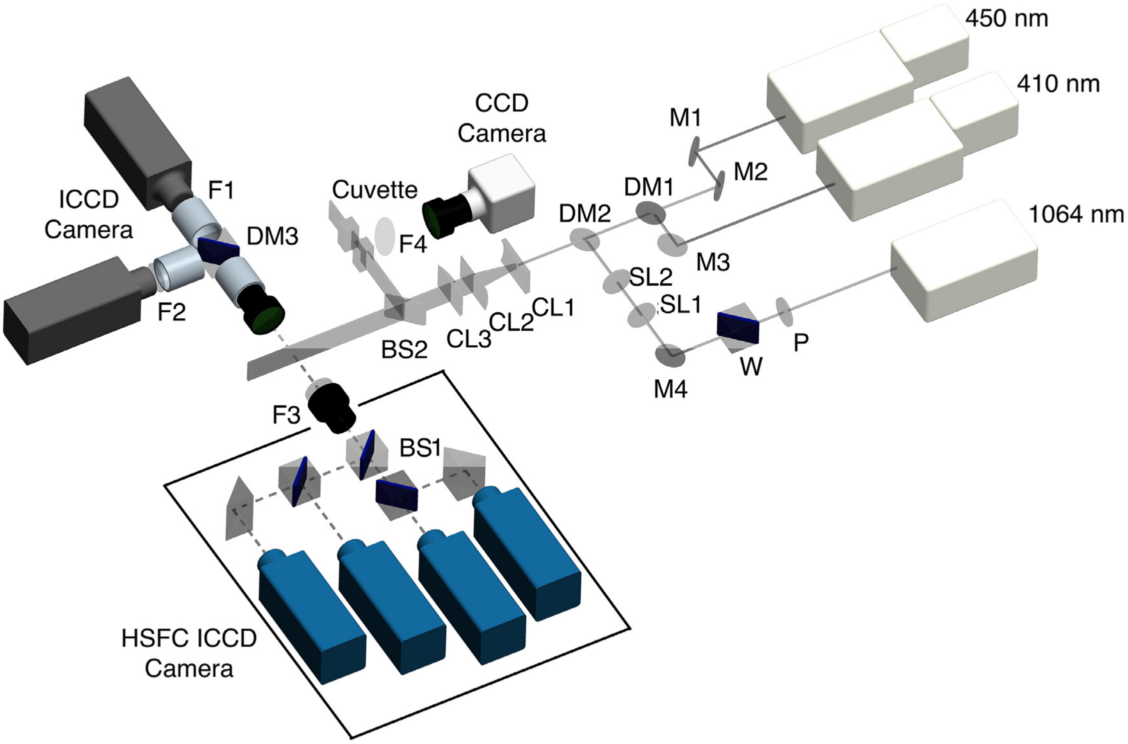

Fig. 1. Schematic diagram of the experimental setup for the combined nTLAF and TiRe-LII measurements. M, mirror; DM, dichroic beam-splitter; W, half-wave plate; P, Glan-laser polarizer; CL, cylindrical lens; SL, spherical lens; F, band-pass filter; BS, prism beam splitter.

the measurements reported by Köhler et al. [17,21] are particularly relevant. This is a non-premixed lifted turbulent ethylene/air jet flame with a relatively simple burner configuration, a well studied fuel of ethylene and sufficient soot concentration for accurate measurement. These characteristics satisfy modelers' needs regarding boundary conditions and flame characteristics [22,23]. Moreover, the authors performed comprehensive optical measurements, including flame temperature using shifted-vibrational coherent anti-Stokes Raman spectroscopy (CARS), flow velocity using particle image velocimetry, f_v using planar laser-induced incandescense (PLII) and planar laser-induced fluorescence (PLIF) of OH and PAHs [17,21]. This relatively extensive data set makes this flame a good candidate firstly for assessment of measurement accuracy through independent measurements, for example, of T and f_v, secondly, for the provision of new insight and data, though the simultaneous (and planar) measurements.

A key statistical parameter that is desired for the above flame is the joint probability density function (PDF) of T and f_v, which is important for accurate predictions of radiation and validation of soot models. Very limited data of the joint PDFs of these two key parameters are available [7–12], which is attributed to the challenging environments encountered by the diagnostic techniques for simultaneous planar measurements. In particular, simultaneous measurements of f_v using laser-beam extinction and soot particle temperature using two-colour pyrometry were performed in piloted ethylene jet flames [7–10] and in JP-8 pool fires [11,12]. This, involves a semi-intrusive, two-ended optical-fibre probe, which integrates over a length of 5 or 10 mm. Alternative non-intrusive optical thermometry methods, such as CARS, are challenging to perform concurrently with the LII technique and have only moderate spatial resolution, typically of a few of millimetres [17,21]. Simultaneous and instantaneous imaging of T and f_v with a high spatial resolution of ~ 400 µm, using nTLAF and PLII, has been demonstrated [18,24]. However, these flames do not have sufficient soot concentration with peak f_v below 1.0 ppm and the temperature measurements by Mahmoud et al. [18] have a relatively high uncertainty (~ 180 K). Significantly, this work does not provide joint PDFs of T and f_v [18,24]. Hence, there is a need for reliable joint PDFs in turbulent sooting flames, such as the chosen target flame studied by Köhler et al. [17,21]. The present study is driven not only by the need for complete data in well characterized flames, but also by the need for comparison of such data with previous measurements of the joint PDFs in other flames. There is also a need for a quantitative comparison of the accuracy of the nTLAF method against the more well-established CARS method. Such a direct comparison is yet to be reported in turbulent sooting flames and is sought after prior to the application of nTLAF in highly turbulent sooting flames to provide dataset for model validation.

The measurements of N_p and d_p are also important to advance understanding of the mechanisms of soot formation and oxidation and validation of soot models. However, available experimental data on N_p and/or d_p are mostly limited to laminar flames [25,26] and are rare for turbulent flames [14], especially that of simultaneous and planar data. While the thermophoretic sampling technique can provide reliable and statistical information [27,28], it has been limited to point-wise measurements. The utilization of Rayleigh scattering and LII imaging for measurements of N_p and d_p suffers from the assumption of scattering behavior for soot aggregates is neglected [29] and has unknown accuracy in non-premixed turbulent flames. Planar measurements of d_p in atmospheric flames with time-resolved laser-induced incandescence (TiRe-LII) has been found to yield good agreement with results obtained with sampling thermophoretic method [30]. However, TiRe-LII has mostly been applied to steady laminar flames [25,26], with one exception of using four sequential LII images in an unsteady premixed flame [31]. Therefore, there is a need to extend the application of the instantaneous planar TiRe-LII technique into the turbulent flames, both to advance the ongoing development of the