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Tomographic Time-Resolved Laser-Induced Incandescence

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Three ultra-high-speed, 10 MHz, cameras imaged the time-resolved decay of laser-induced incandescence (LII) from soot in a turbulent non-premixed ethylene jet flame. Cameras were equipped with a stereoscope allowing each CMOS array to capture two separate views of the flame. The resulting six views were reconstructed into a volumetric soot decay series using commercially available DaVis tomographic software by LaVision. Primary soot particle sizes were estimated from the decay time history on a per voxel basis by comparing measured signals to an LII model. Experimentally quantified soot particle sizes agree with existing predictions and previous measurements.

I. Introduction

A byproduct of inefficient combustion processes, soot is one of the more harmful artifacts of the industrial age. Mitigating soot production requires improved understanding of not only how soot is formed but also what happens to the soot particles chemically and physically as they evolve during the combustion process. Despite significant research, the understanding of these processes remains limited. The development of a diagnostic capable of accurately mapping soot particle size and volume fraction in a turbulent flame would aid the understanding of these processes. Laser-induced incandescence (LII) uses a laser to heat particles and measures the resulting radiative emission. The decay of this emission can then be related to soot particle size [1]. Chen *et al.* [2], recently demonstrated single-shot time resolved laser-induced incandescence (TiRe-LII) imaging using a Shimadzu ultra-high-speed camera. The data were used to determine soot particle sizes based on the decay rate of the soot incandescence intensity. Chen's work forms the basis of the present research.

Modern ultra-high-speed cameras are capable of virtually suspending time, allowing the rendering of extremely fast events. The Shimadzu HPV-X2 cameras used here can acquire 10 million images per second at 400×250 pixel resolution, with a checkerboard interpolation scheme. At atmospheric pressure, soot LII signals typically decay over several hundred nanoseconds and sometimes much longer for larger particles. The ultra-high frame rate allows acquisition of five or more incandescence decay points after laser pulse arrival. The signal decay points can be fitted to the predicted exponential decay, and soot primary particle size calculated.

In this work, TiRe-LII is extended to three-dimensional tomography using three Shimadzu HPV-X2 cameras. Previous work on tomographic LII showed value in using as few as six views to reconstruct a thick slice of the flame

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[3]. To increase the number of views, cameras were equipped with matching stereoscopes. The LII volume was reconstructed from the six images using the commercially available DaVis image processing software [4]. The tomographic volume was then used, in conjunction with model values, to construct a volumetric map of soot particle sizes [5]. Data such as these can be applied for a more accurate understanding of flame conditions leading to increased soot production.

II. Experimental Configuration

The camera configuration, stereoscopes, and flame setup for the tomographic TiRe-LII experiments are shown in Fig. 1 with a closeup photo of a stereoscope shown to the right. The three HPV-X2 cameras are oriented around the flame in ~15-degree increments. The 1064 nm, ~12 ns duration output pulse of a Quanta-Ray Pro-350 injection-seeded Nd:YAG laser was formed into a thick, ~10 mm deep by ~48 mm tall, slab directed into the center of a turbulent non-premixed ethylene jet flame [6]. The center of the laser slab was placed at ~203 mm ($z/D \approx 63$) above the nozzle in the soot growth region of the flame. The laser energy measured at flame center was ~725 mJ or ~151 mJ/cm^2.

The laser-induced incandescence signal is collected via stereoscopes. Fifty-nm-wide bandpass filters centered at 600 nm were inserted between the stereoscopes and cameras. Each camera was equipped with an 85 mm f/4 Nikon lens with a separation between lens and flame of ~550 mm.

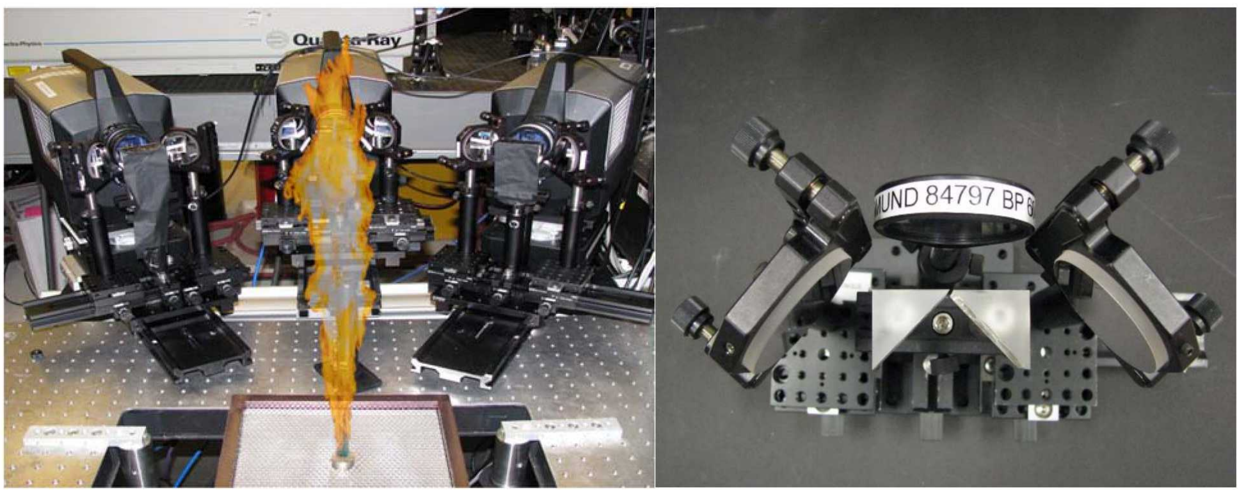

Fig. 1 The tomographic TiRe LII configuration, camera layout, laser slab, and flame location (left) a stereoscope with band pass filter (right).

III. Results and Analysis

Once a set of images were acquired, raw images were cropped and scaled into six separate views as shown in Fig. 2. These images, shown in pseudo color for clarity, provide an example of the LII signal at $t = 0$ ns, coincident with the laser pulse. In Fig. 2 each column displays the pair of images from a single camera and stereoscope configuration. The cameras acquired 256 images at each view; and images prior to the laser pulse were used to account for and subtract background flame luminosity. The LII signal and decay is captured over a span of approximately 10 frames.

The volume was reconstructed using the LaVision DaVis software [4]. Dot-target images were used to determine the precise location of each of the views. The software then uses the processed flame images and the camera calibration to reconstruct the volume using a multiplicative algebraic reconstruction technique (MART). In brief the algorithm reconstructs a volume by equating the signal intensities in the images to their respective volume elements, or voxels. This iterative process continues to adjust and compare the intensities of the voxels to their respective pixels until a convergence criterion is met, in this case when the reconstructed volume does not change appreciably between iterations. The volumes were smoothed by a 3×3 filter between iterations to reduce noise, and the voxel size was ~0.2 mm. The resulting volume then has projections that match the camera views along the same lines of sight. The DaVis processing resulted in ten volumes for each decay point for each run. Fig. 3 displays an example of the resulting tomographic reconstruction. In the top row, four different views, by horizontal rotation, of the reconstruction are shown demonstrating the capability of this technique to identify 3D soot structures. The bottom row shows the view in the last rotation from four different frames demonstrating the decay of the LII signal over time. The following sections will analyze these tomographic reconstructions.

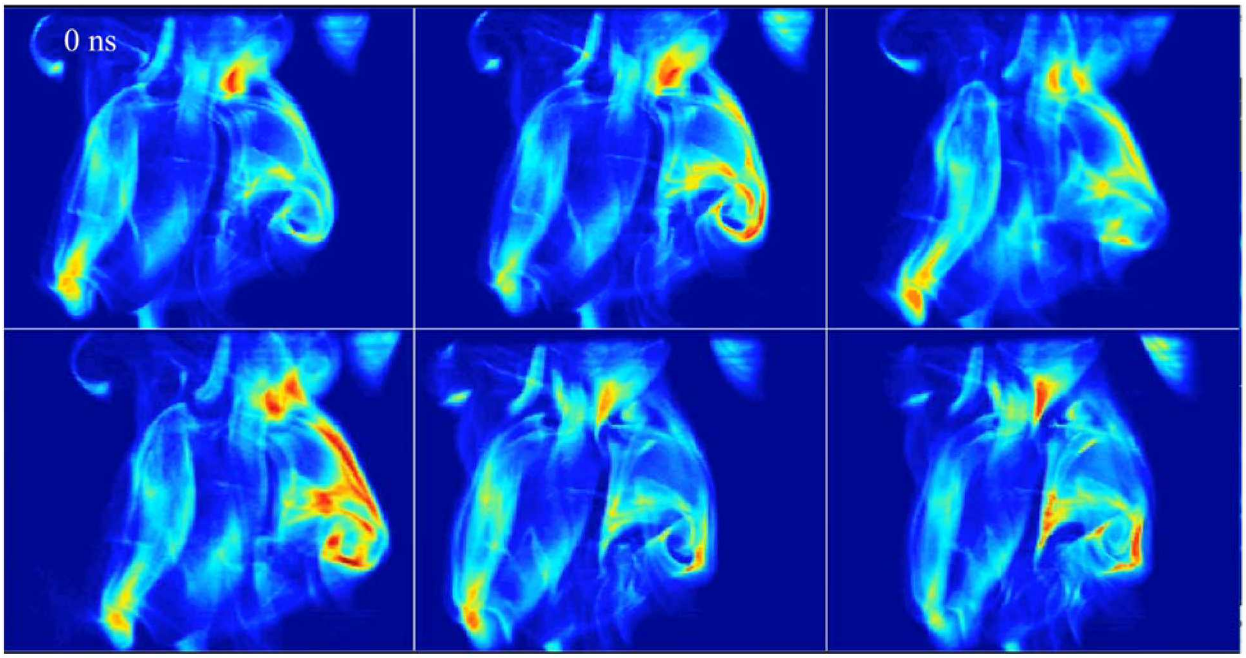

Fig. 2 Example raw images from each of the six views at *t* = 0 ns.

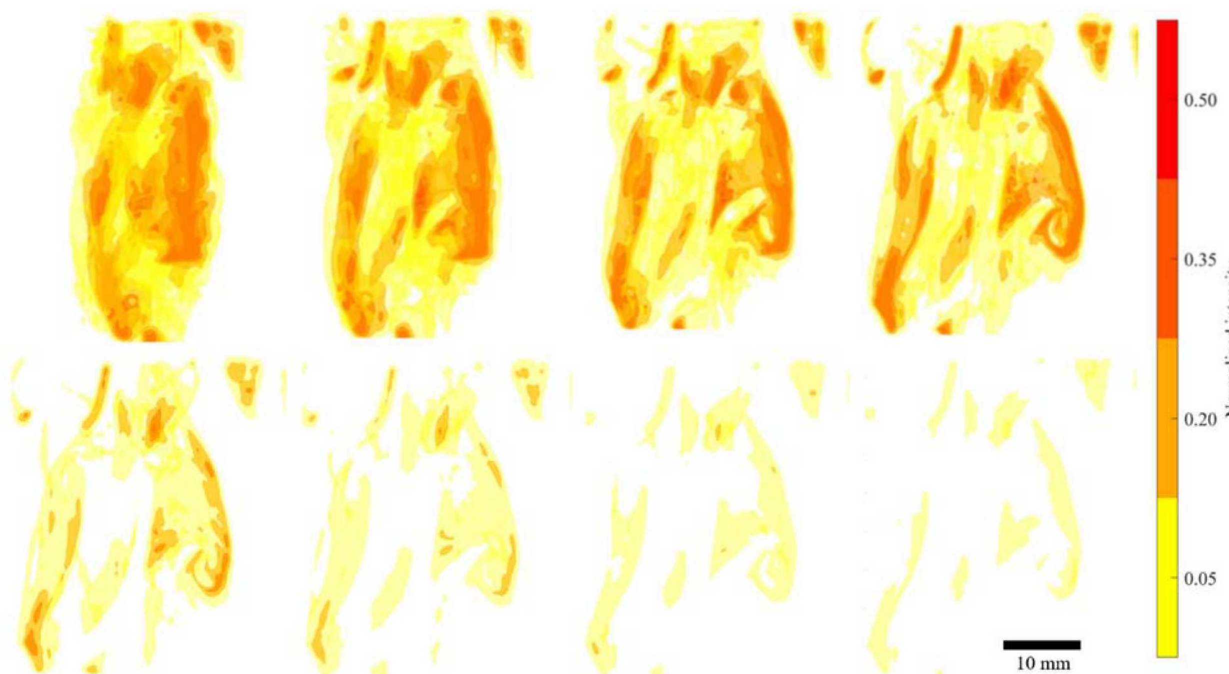

Fig. 3 Example of tomographic reconstruction. Isosurfaces of normalized intensity viewed from four different angles at a single instance in time (top) and depiction of LII signal decay from the perspective of and subsequent to the last angle (bottom).

A. 2D vs 3D TiRe LII

As a qualitative means of validation, the 3D TiRe LII results are compared to 2D TiRe LII results for the same flame conditions, Re = 10,000 and z/D ≈ 60, though it should be noted that the 2D data and 3D data are uncorrelated and were recorded independently. Results of each are shown in Fig. 4, where each row displays a different run and color indicates LII signal intensity. The left two columns show the 3D results. The first column shows an in-plane view of the reconstruction in each run while the middle column shows the orthogonal side view. The dotted line indicates the corresponding location relating the two views. The right column shows 2D results. These examples show qualitative agreement of the reconstructed 3D and 2D structures. It appears the spatial resolution is slightly degraded in the 3D results while the signal to noise ratio is improved. In the 3D results the out-of-plane resolution is also likely inferior to the in-plane resolution as is the case in 3D imaging techniques, based on the locations of the views.

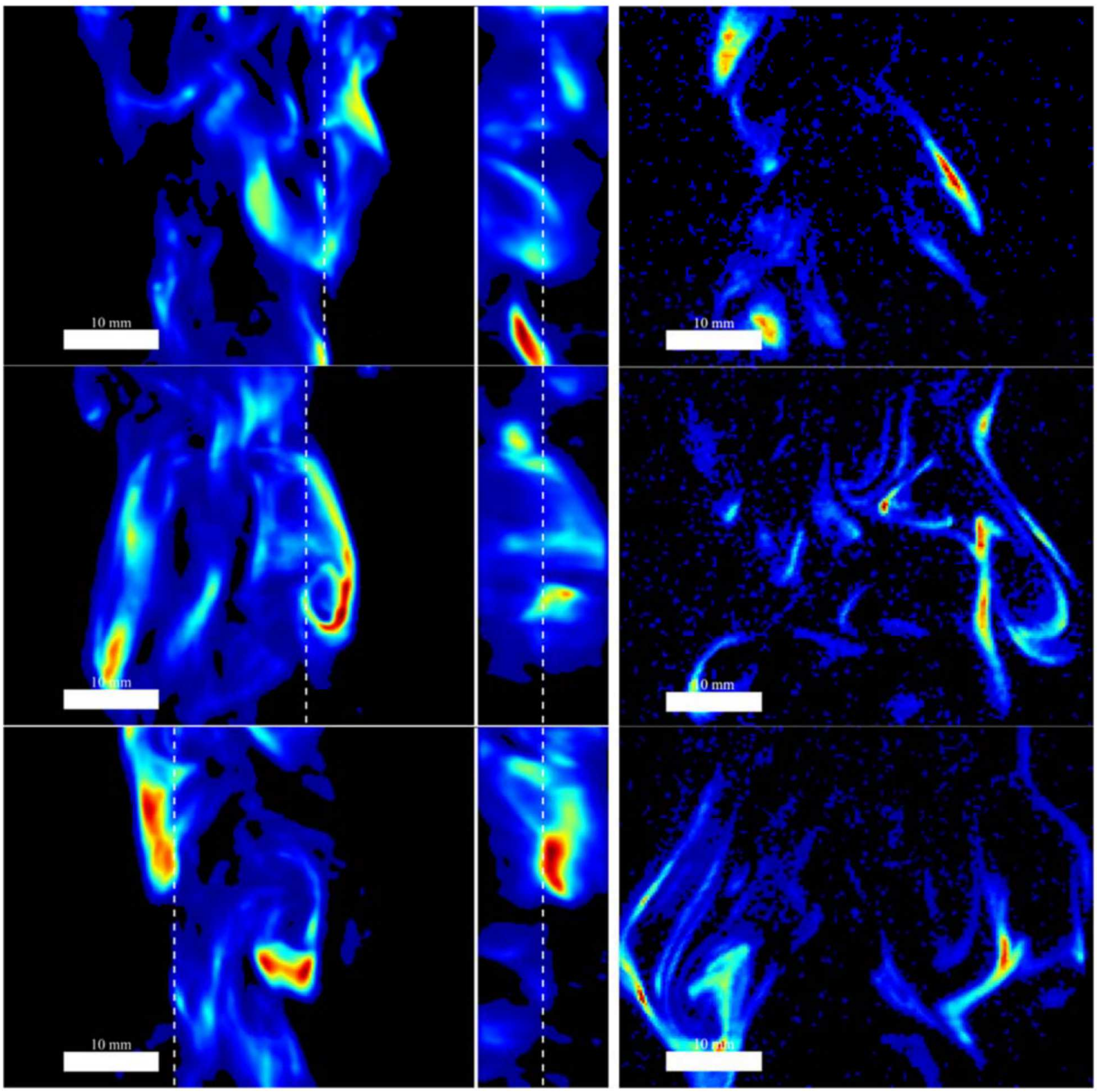

Fig. 4 TiRe LII 3D (left) and 2D (right) showing qualitative agreement for an example case where Re = 10,000, *z*/*D* ≈ 60 for three different runs.

B. Primary soot particle diameters

An array of voxel values in the three-dimensional reconstruction was created at each of ten time points during the soot incandescence decay. These values were fit to a LII model based on Cenker's work on prediction of soot production in turbulent flames [5, 7]. Assuming that all soot primary particles are spheres, the LII model predicts the particle temperature, hence the blackbody radiation, for any size of particle for any given time after the laser pulse by solving the energy and mass balances. In this work, theoretical LII signals of soot particles from 4 nm to 99 nm in diameter are simulated with the model. The collection of simulated data is called a signal library. Signal decay was compared, via a look up table, to these libraries and the closest matching soot primary particle diameter was assigned to the voxel as shown graphically in Fig. 5. Here, the measured LII signal for an example voxel is indicated by the gray dot for each frame in which signal was measured. These intensities are overlaid on the model curves of decay for a range of particle sizes shown in the colored curves; for this particular voxel the measured particle size was 16 nm. The left section of Fig. 6 shows the resulting volumetric map of particle size created by repeating this process for all voxels. Four slices at varying heights are detailed in the plot to the right. Soot particles sizes ranged from 4 nm (minimum value simulated by the model) to nearly 100 nm with a peak value of roughly 10–15 nm.

For an accurate comparison of measured LII signal decay with simulated libraries, information about local conditions (initial temperature, gas composition, pressure, optical properties of soot, morphology) are necessary for the LII modeling. Because these spatially and temporally varying conditions are not exactly known for this turbulent non-premixed flame, there were six libraries created with four different flame temperatures ranging from 1450 to 1750 K and three soot absorption functions, $E(m)$, ranging from 0.2 to 0.4. The comparison produced very similar results over the varying model input parameters showing that soot particle size is insensitive to slight changes in these parameters. The reported predictions in this paper are based on simulations with 1550 K flame temperature and $E(m)$ of 0.4.

Fig. 7 displays a probability density function of the measured soot particle diameters complied from ten runs at Re = 10,000 and $z/D \approx 60$. This diameter distribution agrees with 2D results at the same conditions in the growth region of the flame [2]. Future parametric studies using 3D TiRe LII will also consider the oxidation region of the flame to allow a more extensive comparison.

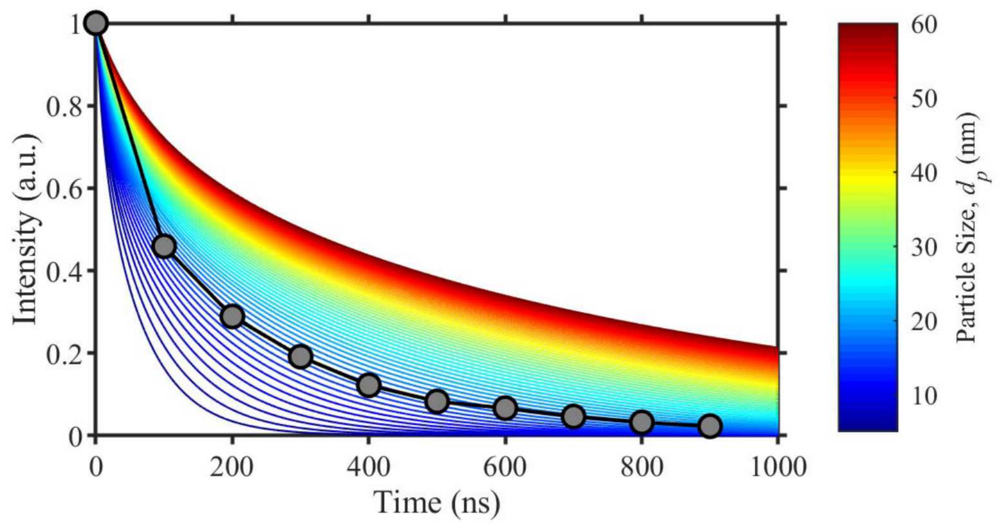

Fig. 5 Signal decay at a single voxel (gray dots) overlaid on the model prediction of signal decay for a range of soot primary particle diameters.

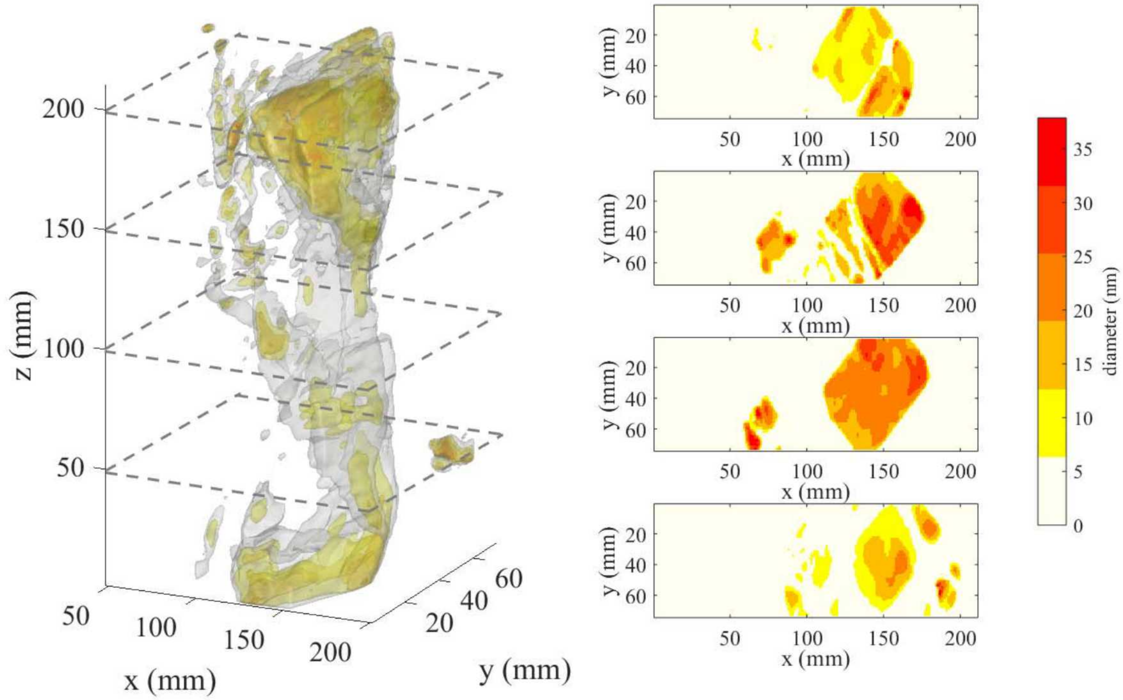

Fig. 6 Isosurfaces (left) and horizontal slices (right) of primary soot particle diameters in turbulent ethylene jet flame.

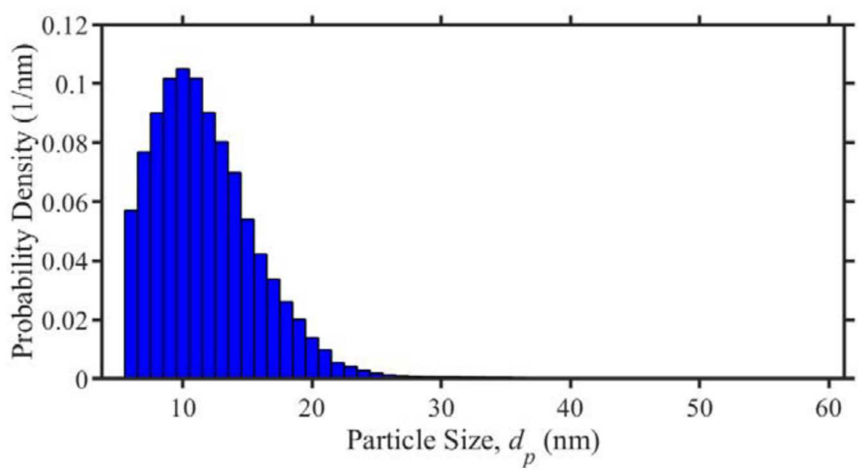

Fig. 7 A histogram of soot particle diameters in the flame studied in Fig. 6.

IV. Conclusions and future work

In this work a method of determining soot primary particle diameter in three dimensions with improved accuracy has been developed. Volumetric determination of soot particle sizes has been demonstrated and the experimental results show agreement with models and previous planar TiRe LII measurements [8-13]. Future work in development of this technique could include several experimental improvements and extensions. Improvements include resolution of the identified problems with the laser timing and characterization of shot to shot laser energy. Extensions include the addition of a parametric study to allow examination of 3D TiRe LII at varied Reynolds number, laser fluence, and flame regions. Reynolds numbers of between 10,000 and 25,000 would be of interest based on the characterization of the flame by Zhang [6]. Fluences up to 0.15 J/cm^2 could be examined given the expected substantial evaporation at higher values. Axial positions near the inception region, at the brightest flame region and near the tip of the flame would allow capture of soot particle size growth and decay. The addition of simultaneous planar LII utilizing the unused frames of one of the cameras already used in the tomographic measurements would additionally allow direct comparison of results. Finally, many runs at each condition would allow statistical convergence of results.

The development of tomographic time resolved laser-induced incandescence demonstrated in this work enables improved measurements of the 3D distribution of soot particle sizes. These measurements can help to expand the understanding of soot production and development and play a critical role in improving inefficient combustion processes.

Acknowledgments

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