High-Speed, Two-Dimensional Temperature Imaging in Turbulent Non-premixed Jet Flames Using Planar Rayleigh Scattering

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In this paper we describe recent improvements made within our research group to obtain high-speed (10 kHz), two-dimensional temperature imaging in turbulent non-premixed jet flames using planar Rayleigh scattering in conjunction with a new, high-repetition-rate, high-energy pulse-burst laser system (HEPBLS). The HEPBLS, which can output ultra high pulse energies at 10 to 50 kHz (e.g., ~1 Joule/pulse at 532 nm at 10 kHz) and long burst durations (e.g., up to 25 ms), allows for high-resolution, long-duration imaging of two-dimensional, time-correlated temperature fields in turbulent flames. The combination of the high-energy output from the HEPBLS and an optimized optical collection system allows for the use of an un-intensified CMOS camera, which greatly improves the spatial resolution and the signal-to-noise ratio as compared to previous high-speed, two-dimensional temperature imaging obtained within our group using an intensified CMOS camera (Patton et al., 2011). This allows detection of smaller-scale turbulent features (e.g., turbulent fluctuations) as well as improved measurements of temperature gradients. Results from laminar non-premixed flames are used to determine “single shot” signal-to-noise ratios (up to 90 in air and 35 at 2000 K) and the improvements enabled by eliminating the need for a high-speed image intensifier. Finally, sample 10-kHz imaging results are shown for the well-characterized DLR flames A and B (CH₄/H₂/N₂) at Re = 15,200 and 22,800, respectively, to highlight the potential usefulness of the time-correlated, two-dimensional temperature data.

1. Introduction

Turbulent combustion processes account for more than 85% of all energy production in the world with applications ranging from transportation to power generation. Thus, increased efficiency and decreased emissions for combustion systems will continue to be important research goals for the foreseeable future. In order to achieve these stringent demands, improved understanding of the various aspects of turbulent combustion, including reactant mixing, ignition, and turbulence-chemistry interaction, will be necessary through advanced experimental and computational research. In terms of experiments, laser diagnostics allow for non-intrusive measurements of velocity and scalars (e.g. temperature and species concentrations) and already have proven invaluable in identifying important and rate-controlling physical and chemical mechanisms within turbulent combustion systems (Eckbreth, 1996, Barlow et al., 2007).

The time-varying temperature field is of particular importance because it plays a key role in the majority of chemical and physical processes occurring within turbulent combustion environments. Finite-rate chemical kinetics are temperature-dependent and some kinetic processes including soot and NOx formation are strongly dependent on local temperature fluctuations. Local flame temperature can heavily influence heat transfer and is a key quantity in ignition, local flame extinction, and re-ignition. Also, it can be argued that the turbulent temperature field is closely linked and correlated with the mixture fraction field for flame cases far from extinction (Everest et al., 1995, Wang et al. 2005). The mixture fraction ($\xi$) and the scalar dissipation rate ($\chi = 2D\nabla T \cdot \nabla T$) describe the molecular mixing within in the flame and are critical parameters for describing non-premixed and partially premixed combustion. For flames that operate far from extinction, the state relation $T = T(\xi)$ exists, implying a proportionality between the rate of thermal mixing with the rate of scalar dissipation. Thus, measurements of the temperature field (and its derivatives) may be important in yielding information on the underlying structure of the molecular mixing processes as well as the thermal transport and mixing processes.

For turbulent combustion, planar techniques are highly desired in order to spatially resolve the underlying structure of the temperature field. Of the many suitable laser-based thermometry approaches (Eckbreth, 1996), planar Rayleigh scattering is the most widely used technique for multi-dimensional temperature imaging. Rayleigh scattering...
thermometry has been used for more than 30 years, starting with 0D and 1D measurements by Pit et al. (1976), Smith (1978) and Dibble and Hollenbach (2005) and continuing with recent high-resolution planar Rayleigh scattering-based temperature imaging in turbulent non-premixed flames (Frank et al., 2009, Frank et al., 2010). While these measurements have been performed with very high spatial resolution, previous multi-dimensional temperature measurements using Rayleigh scattering have been limited in temporal resolution, that is, any two consecutive images have been temporally uncorrelated. Recognizing that turbulence is inherently stochastic, flow field scalars such as temperature should be resolved in both space and time in order to capture the dynamic nature of turbulent flames. This requirement dictates that the data acquisition rate of the scalar fields is much greater than typical time-scales of the turbulent processes ($\gg$ 1 kHz).

Recent work within our group (Patton et al., 2012) demonstrated two-dimensional, 10-kHz temperature measurements in a series of turbulent non-premixed jet flames using planar Rayleigh scattering and pulse burst technology (Thuraw et al., 2001). The previous pulse burst system output was approximately 200 mJ/pulse at 532 nm, which was sufficient to measure the instantaneous temperature field at 10 kHz. However, the previous laser system was limited to burst durations of 1 ms, which resulted in a limited ten-image sequence. In addition, the pulse energies, while unprecedented for kHz-rate laser systems, required the use of a high-speed image intensifier, which is known to degrade spatial resolution (Weber et al., 2011) and limits the achievable signal-to-noise ratio.

This paper describes the use of a new high-energy pulse burst laser (HEPBLS), developed at Ohio State, to acquire multi-kHz temperature imaging in turbulent non-premixed flames, based on high-speed planar Rayleigh scattering. The new HEBLS has the capability of outputting sufficiently higher pulse energies at 532 nm (e.g., ~ 1 Joule/pulse) at repetition rates exceeding 10 kHz. In addition, burst durations exceeding 10 ms are demonstrated, with the existing capability of achieving durations > 25 ms. The higher laser pulse energies have allowed the use a high-speed CMOS camera only (no intensifier), which greatly improves spatial resolution and signal-to-noise ratios as shown below.

2. Methods

2.1 Rayleigh Scattering

Planar laser Rayleigh scattering-based temperature imaging has been widely used within turbulent premixed, partially-premixed, and non-premixed flames. Laser Rayleigh scattering is non-intrusive diagnostic technique that describes the scattering of light from a molecule whose diameter is much smaller than the wavelength of the incoming light. The emitted Rayleigh scattering intensity can be written as

$$I_{\text{RAY}} = A I_o n \sigma_{\text{mix}}$$  \hspace{1cm} (1)

where $A$ is a constant which describes the collection optics and scattering angles, $I_o$ is the incident laser intensity, $n$ is the number density of the scattering molecules, and $\sigma_{\text{mix}}$ is the mixture averaged differential scattering cross-section which is given by $\sigma_{\text{mix}} = \sum_{i=1}^{N} X_i \sigma_i$, where $X_i$ and $\sigma_i$ are the mole fraction and differential scattering cross-section of species $i$, respectively. Substituting the ideal gas law ($n = P/v_{\text{RT}}$, where $P$ is pressure, and $v$ is the Boltzmann constant) into equation (1) yields

$$I_{\text{RAY}} = A I_o \frac{P}{kT} \sigma_{\text{mix}}$$  \hspace{1cm} (2)

The constant $A$ is typically accounted for by normalizing the Rayleigh signal from the flame by the Rayleigh signal of a known temperature and species concentrations such as room temperature air. The fuel mixture for the flames considered in this paper is comprised of 22.1% CH₄, 33.2% H₂, and 44.7% N₂, which results in a mixture-averaged scattering cross section that varies by less than 3% throughout the flame. This allows the determination of the flame temperature without the simultaneous measurement of the local species concentrations. In this manner, the temperature is determined from

$$T = T_{\text{ref}} \frac{I_{\text{ref}}}{I_{\text{RAY}}}$$  \hspace{1cm} (3)
where, $I_{ref}$ is the reference Rayleigh signal and $T_{ref}$ is the temperature of the room temperature air. It should be noted that although frequently utilized at low repetition rates, planar Rayleigh scattering requires high pulse energies, which are not available from current commercial kHz-rate laser systems. Thus, the custom HEPBLS, as described below, facilitates these measurements.

2.2 HEPBLS

The high-energy pulse-burst laser system (HEPBLS) was recently described by Fuest et al. (2012) and is shown schematically in Fig. 1. The HEPBLS is a master oscillator, power amplifier (MOPA) system that amplifies the low-energy output (~10 $\mu$J/pulse) of a continuously running single-frequency laser (PO, which serves as the master pulsed oscillator) in a series of five, custom, long-duration, flashlamp-pumped Nd:YAG amplifier stages with total system gain > $4 \times 10^5$. The repetition rate of the pulsed oscillator determines the pulse spacing within the burst, while the flashlamp discharge duration determines the overall length of the burst and the number of amplified pulses. The 1064 nm output from the PO is a narrow linewidth (~2 GHz), pulsed Nd:YVO$_4$ laser with a pulse duration of 25 ns and variable repetition-rate output ranging from 1 to 50 kHz. The continuous train of pulses is first amplified in a series of two, flashlamp-pumped amplifiers arranged in a double-pass configuration (4- and 6.3-mm diameter rods, respectively). After two stages of amplification, sufficient energy exists such that the 1064-nm pulse trains are focused into a phase conjugate mirror (PCM). The PCM, which has been described previously in detail (Thurow et al., 2001; Fuest et al., 2012), is an optical cell filled with a high index of refraction liquid (FC-75) which uses the process of stimulated Brillouin scattering as an intensity filter and stops the growth of Amplified Spontaneous Emission (ASE) which would limit energy gain in later amplifier stages. When the incident beam intensity is above a minimum threshold it is coherently retro-reflected and anything below that threshold (e.g. ASE) passes through the cell to a beam dump. The retro-reflected pulse train then passes through a 50/50 beam splitter to create two parallel legs. By dividing the system into two legs, the available overall gain and the versatility of the system is increased. The 3rd stages, which employ 9.5-mm-diameter rods, also are arranged in a double-pass configuration. Stages 4 and 5, which use 19.5 mm-diameter Nd:YAG rods are operated in a single-pass configuration with a 90-degree quartz rotator placed between them to help reduce birefringence effects caused by the thermal gradients within the rods.
The output of the fifth and final amplifier stage is greater than 1 Joule/pulse for each leg at 1064 nm for a total output energy that exceeds 2 Joules/pulse at 10 kHz with an RMS of the pulse-to-pulse fluctuation within the burst of less than 5% as described in Fuest et al. (2012). In this work, a single leg, operating at approximately 70% of output capacity is used to generate the 532-nm output used for the Rayleigh scattering measurements. The 1064-nm output passes through two type I LBO doubling crystals to generate > 500 mJ/pulse at 532 nm. A typical 10-ns, 532-nm energy trace at 10 kHz is shown in Fig. 2. In Fig. 2, the gain settings were lowered such that the average pulse energy was ~ 430 mJ. Similar to the fundamental output, the 532-nm output exhibits low pulse-to-pulse fluctuation within the burst with an RMS value of < 7%. Future work will consist of combining the two 532-nm output legs for > 1 Joule/pulse generation at 532 nm.

2.3 Optical Setup

A schematic for the optical setup used in the present work is shown in Fig. 3. The 532 nm output from the HEPBLS is formed into a 15 mm x 0.20 mm laser sheet by a single, plano-convex cylindrical lens (f = 750 mm). The laser sheet thickness (defined as the full-width at half maximum, FWHM) was determined by rotating the cylindrical lens 90 degrees and imaging the laser sheet profile. The high-speed Rayleigh scattering images are collected with a high-speed CMOS camera (Vision Research, Phantom V711). In order to maximize the collected Rayleigh scattering signal, a large, (f = 160 mm, D = 80 mm) achromat lens was coupled with a 50 mm f/1.2 Nikon camera lens. This combination results in a collection f-number of 2 and a magnification of 0.31 and an imaged area of ~ 60 µm/pixel. At 10,000 frames/second, the camera resolution is 1024x688. A second high-speed CMOS camera is shown Fig. 3, which images a uniform region in air to correct for variations in laser sheet intensity.

The previous high-speed planar temperature measurements, as reported in Patton et al. (2012), involved a CMOS camera that was coupled to a high-speed image intensifier (LaVision Inc., HS-IRO). The lower pulse energies from the previous generation pulse burst laser system dictated the need for the HS-IRO, which increased signals levels to suitable levels, but degraded the spatial resolution. The higher pulse energies and improved optical setup reported in this paper allow the acquisition of high-quality planar Rayleigh scattering measurements without the use of an HS-IRO, thus improving spatial resolution and signal-to-noise ratios.

2.4 Flame conditions

Both the laminar and turbulent flames considered in this study are simple jet flames issuing into a low-speed co-flowing stream air (~0.3 m/s). The turbulent flames are the well-known “DLR” flames, which serve as benchmark flames within the International Workshop on the Measurement and Computation of Turbulent Nonpremixed Flames (TNF Workshop) (Barlow, 1996-2006). The fuel used for both the laminar and turbulent flames consists of 22.1%CH₄, 33.2% H₂, and 44.7% N₂. The fuel issues from an 8-mm diameter tube at 43.2 m/s for DLR flame A (Re = 15,200) and 63.2 m/s for DLR flame B (Re = 22,800) into a 30 x 30 cm² co-flow of air. The laminar flame considered in this study is a Re =1500 non-premixed flame. The jet-flame assembly is mounted on two high-precision translation stages that allow for translation in both the axial and radial directions. The co-flowing air is filtered, which is essential to remove dust particles, as the Mie scattering from such particle would completely mask the Rayleigh signal.

3. Results and Discussion

3.1 Improved Spatial Resolution
As noted in Sec. 2, the high pulse energies of the HEPBLS system, in combination with an improved optical collection system, allow for sufficient collection of the Rayleigh scattering signal such that an high-speed image intensifier (IRO) is not required as in previous studies (e.g., Patton et al., 2012). In this section, we will describe the benefits in terms of increased spatial resolution and signal-to-noise of using a CMOS camera only (without the IRO). While the use of an IRO boosts the collected Rayleigh signal, it is well known that the two-stage intensifier degrades the spatial resolution of the measurements due to non-localized gradient blurring (Weber et al., 2011). In addition, the use of an image intensifier can limit the achievable signal-to-noise ratios due to photon multiplication and spurious noise contributions. Figure 4 shows two images of a USAF 1951 resolution target as imaged by the combination of a CMOS + IRO and a CMOS camera only. The IRO gain settings are identical to that used previously (Patton et al., 2012) and the exposure time is adjusted such that the signal level (“counts”) is comparable to the maximum signal levels from the previous work (Patton et al., 2012). For the “CMOS only” case (i.e., no IRO), the exposure time is adjusted such that the peak-collected signal is matched to the Rayleigh signal levels from the current Rayleigh scattering experiments reported below. Additionally, the field-of-views for both images are identical (41 mm x 61 mm before cropping) and the images are displayed with the same dynamic range; that is, the ratio of the average signals corresponding to “white” and “black” (before normalization) in Fig. 4 are the same. From Fig. 4 it is clear (and expected) that the “CMOS only” images display much higher spatial resolution as compared with the CMOS+IRO images. As one example, a section displaying the smallest features of the USAF 1951 target is extracted and magnified by 300% to highlight the improved spatial resolution. Almost all of the individual lines from the line-pairs in the zoomed-in section of the resolution target are indiscernible from the CMOS+IRO image whereas many of those same lines are quite distinct in the CMOS only image. In addition, it is noted that while the actual signal levels are higher in the CMOS+IRO images (3000 vs. 1000 counts). The signal-to-noise is less than the CMOS only case as expected.

To further investigate the two camera systems’ response as a function of spatial frequency, Fig. 5 shows normalized intensity profiles taken through various bar patterns within the USAF 1951 target that correspond to different bar thicknesses and number of line pairs/mm. Each plot in Fig. 5 displays the normalized intensity vs. normalized spatial position, Δx/L, where Δx is the pixel spacing and L is the local bar thickness. The dashed lines represent the ideal intensity distribution of any given bar pattern, the red lines represent the measured profiles from the CMOS only image, and the blue lines represent the measured profiles from the CMOS+IRO image. The line thicknesses, L, over which the signals levels were obtained are L = 446 μm, L = 280 μm, L = 198 μm, and L = 111 μm.

For all bar thicknesses, the effect of the IRO is easily observed. Even for the largest bar thickness (L = 446 μm), the CMOS+IRO profile shows reduced contrast (or modulation); that is, the maximum and minimum signals do not reach a value of 1 or 0, respectively. At L = 111 μm, no contrast is observed for the CMOS + IRO, while the contrast for the CMOS is > 0.6 (“ideal” contrast = 1).

A more rigorous way to show the improved spatial resolution of the current optical configuration is by estimating the modulation transfer function (MTF) of the two imaging systems from the USAF resolution targets. The MTF is defined as
MTF = \frac{M_{\text{image}}}{M_{\text{ideal}}} \quad (4)

where $M$ is the modulation and is defined as

$M = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \quad (5)$

where $I_{\text{max}}$ is the maximum intensity throughout the repeating pattern and $I_{\text{min}}$ is the minimum intensity throughout the repeating pattern. For a normalized signal as shown in Fig. 5, $M_{\text{ideal}} = 1$. Figure 6 shows the estimated MTF for both the CMOS and CMOS+IRO image cases. The MTF value for the CMOS+IRO camera is around 20% at approximately 3.5 line pairs/mm. The same MTF value is achieved for the CMOS only camera setup at approximately 9 line pairs/mm. From these results, we can infer that the smallest feature which is identifiable is between 120 µm and 200 µm for the CMOS + IRO, and is ~ 60 µm (limited by the pixel projection area of the camera). The higher pulse energies from the HEPBLS in conjunction with the improved optical setup allow for the ability to take advantage of increased spatial resolution that comes with using a CMOS camera only as opposed to using an intensified CMOS as in the previous high-speed temperature imaging studies from our group.

3.2 Sample Temperature Results

Figure 7 presents an instantaneous temperature image acquired in the Re = 1500 flame. The full image height is 14 mm, but only 9 mm are shown for compactness. The image spans approximately 6 tube diameters in the radial direction. Shown beneath the 2D temperature image is a plot of the radial temperature profile extracted from the axial position indicated by the white dashed line. Also shown on the same radial plot is a red dashed line, which indicates the adiabatic flame temperature ($T_{\text{ad}}$) for the current fuel/oxidizer combination. Since the instantaneous image is from a laminar flame with uniform low- and high-temperature regions, estimations of single-shot signal-to-noise ratios (SNR) can be obtained. From the uniform “air” regions ($r/d > 2.5$), the SNR, which is defined as the mean temperature divided by the RMS fluctuation of the same region, is approximately 90. Similarly, the 9-mm axial profile at $r/d \sim 1.3$ represents a nearly uniform, high-temperature region. At this location, the SNR is deduced as ~ 35 at $T = 1900$ K. These are significant improvements as compared to our earlier work (using an IRO) in which the SNR was estimated as 35 and 11 at ambient and $T \sim 1800$ K (Patton et al., 2012). Figure 8 shows two sample turbulent flame images from DLR flames A and B. The images on the left are from the previous high-speed temperature study using the previous generation of PBLS in conjunction with an intensified CMOS camera and the images on the right are from the current HEPBLS in combination with an un-intensified CMOS camera. The centerline regions from both DLR flame B images are zoomed in and shown below the DLR flame B images. The excerpts are converted to grey scale and are displayed with a 30% increase in contrast to highlight the small-scale structures. The substantial improvements in both spatial resolution and SNR with the new system are apparent from the turbulent flame images shown in Fig. 8. The small-scale structure is essentially
lost in the intensified CMOS image on the left whereas a rich set of small-scale structures are clearly identified in the CMOS only images.

In addition to outputting higher pulse energies, the new HEPBLS also provides extended burst durations as compared to the previous generation of pulse burst lasers. Pulse burst durations of greater than 20 ms have been recorded with the HEPBLS and durations of 10 ms are reported in this paper at repetition rates of 10 kHz. This longer record length allows for more detailed investigations concerning combustion dynamics and also will allow for unique spatio-temporal statistics to be deduced within turbulent flame environments.

Figure 9 shows a partial sequence of temporally-correlated temperature images in DLR flame A (Re = 15,200) at an axial position of x/d = 10. The dimensions for each image are approximately 40 x 14 mm$^2$ and the temporal spacing between images is 100 µs. The images were obtained with 500 mJ/pulse at 532 nm, which

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**Figure 8 – (Left) Previously-reported turbulent flame images from a 10-kHz image sequence (Patton et al., 2012). (Right) Instantaneous turbulent flame images using the new HEPBLS and CMOS camera only. The single frame images are extracted from the 10-kHz image sequences shown below in Figs. 9 and 10.**

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Fig. 9 – 40-frame (of 100), 10-kHz sequence of the temperature field in a turbulent (Re = 15200) non-premixed jet-flame issuing into air. Fuel mixture is 22.1% CH4 / 33.2% H2 / 44.7% N2 and Re = 22,800 (DLR B Flame). Image sequences are shown for an axial position of x/d = 10.
corresponded to 40% of the total output capability of the HEPBLS. The image sequence highlights the dynamic nature of the thermal field within turbulent non-premixed jet flames. The high temperature regions of the flame are seen to fold, roll and sometimes separate throughout the course of the image sequence, indicating the strong interaction with the turbulent flow field. Figure 10 shows a second example of a recent 10-kHz temperature sequence obtained within the DLR flame B (Re = 22,800). Similar to Fig. 9, only 4 ms of “real time” data is presented, although the full image sequence corresponds to > 10 ms. It is well known that DLR B is near extinction (Meier et al., 2000) and Fig. 10 displays several examples of strong turbulence-chemistry interaction. From this image sequence, features such as the formation of “flame holes” (cold gas pockets surrounded by hot gas; i.e., image 7 -16) and the upstream propagation of a high-temperature reaction zone are clearly seen, showing the time-varying (dynamic) nature of thermal mixing and the introduction of steep thermal gradients. Image sequences, such as these, will provide a new understanding of turbulent thermal mixing and flame dynamics.

The long pulse burst duration also allows for the extraction of novel simultaneous spatial and temporal flame statistics, which will be the subject of future work. In this manner, Fig. 11 presents temporal traces from the DLR A temperature sequence shown in Fig. 9. Figure 11 shows the location of two virtual “probes” on a temperature image from DLR flame B. The two “probes” are located at the same axial position (~x/d = 10) but at different radial positions. One “probe” is located at r/d = 1.33 and the other is located at r/d = 1.67. The temperature traces illustrate the different time scales present within the flame at the two radial locations. The “probe” at r/d = 1.33 fluctuates more vigorously with higher temperature gradients than the “probe” at r/d = 1.67. Since the high-speed temperature images characterize the temperature field in two spatial dimensions, similar “probes” can be placed anywhere within the 2D plane. From a
large number of traces at various key locations with the reacting flow it is conceivable that novel and important multi-point, multi-time, scalar statistics can be deduced.

4. **Brief Conclusions**

In this work, we have described the utility of a new high-energy pulse burst laser system (HEPBLS) in obtaining temporally-correlated, planar Rayleigh scattering measurements of temperature in a laminar and turbulent jet flames. The higher laser pulse energies (as compared with a previous-generation PBLS) in combination with improved new, high-throughput optical setup have permitted the acquisition of 10-kHz temperature images using a CMOS camera only. Such an imaging system has led to significantly improved spatial resolution and signal-to-noise ratios. This improved spatial resolution allows for the observation of the small-scale thermal fluctuations (in both space and time). The long burst duration allows for the observation of combustion dynamics and transient physics occurring at many different time scales. Such observed events included the formation and dissipation of thermal cold zones surrounded by high temperature regions. These could be indicative of local flame extinction within the flow. Furthermore, the temporal record of the two dimensional temperature can be used to provide new, temporally-based statistical information at various spatial positions within the turbulent flames.

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**References**


