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High repetition rate planar laser induced fluorescence of OH in a turbulent non-premixed flame

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Abstract. High speed planar laser induced fluorescence (PLIF) imaging of the OH radical is presented in a turbulent nonpremixed methane-air flame. Sequences of up to eight successive PLIF images could be resolved sequentially at several kHz repetition rates. Turbulent flow phenomena such as vortex formation and air entrainment in the flow could be visualised and their development tracked in real time. Turbulence/chemistry interactions such as local extinction and re-ignition and their temporal evolution can be studied with the presented system.

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The interactions between flow phenomena and chemistry taking place in turbulent combustion processes pose a severe challenge to modern combustion research [1]. Although much insight into these processes is gained from statistical, time averaged data [2], time and spatially resolved measurements of relevant scalars are needed for a better understanding of the evolution of turbulent reactive structures. High speed Mie scattering [3] has been used to this end but it requires seeding of foreign species into the flow. Schlieren videography [4] has also been applied but is a line of sight technique. Planar laser induced fluorescence (PLIF) of OH, on the other hand, has been shown to be a valuable tool to study flame structures [5] since OH is one of the most important chemical intermediates occurring in combustion systems of interest. Its local concentration is a complex function of molecular transport processes and the prevailing flow field characteristics. Sequential imaging of OH thus gives direct clues on the evolution of turbulence-chemistry interactions, but this is a very complex experimental task: The repetition rates of the laser and detection systems must be matched to the characteristic times of the flow (10's to 100's of kHz are required for many flames of interest). Multiple high power laser pulses in the UV spectral region are required for OH PLIF excitation and the detector needs good sensitivity as well as time resolution to yield useful data. Sequential PLIF of OH has been performed in the past [6–8] but technology available at the time has either limited temporal and spatial resolutions of these measurements, or the number of sequential images that could be captured. In this paper we report on the first measurement of up to eight sequential PLIF OH images in a turbulent nonpremixed methane air flame which were recorded at several kHz repetition rates giving "cinematographic" insight into turbulent reactive flow phenomena.

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1 Experimental

1.1 The flame

The experiments were performed in a non-premixed methane air flame consisting of two concentric tubes of 30 cm length. Air was passed through the inner tube having 4.5 mm diameter, fuel was passed through the outer tube having 7 mm diameter. Flows were controlled with standard rotameters and set to $21 \pm 3\,\mathrm{ms}^{-1}$ for air and $3.3 \pm 0.5\,\mathrm{ms}^{-1}$ for methane.

1.2 The laser system

The laser source consisted of a custom built unit (BMI) of four individual and independent Nd:YAG lasers each featuring an oscillator and a single amplifier stage. Each laser head was fitted with a double pulse option (DPO) where the Pockels cell can be pulsed twice in rapid succession while the flashlamp is firing. This allows the extraction of up to two laser pulses from each cavity with a selectable time separation of between 25 and 145 μs. All cavities could be triggered independently to arbitrary external events resulting in pulse bursts of up to 8 individual pulses. The output was frequency doubled to 532 nm using 4 KdP crystals and combined using a special beam combining scheme (BMI) resulting in minimal loss of energy. In 8 pulse mode output energies were 270 mJ per pulse. A commercial dye laser (Continuum) operating on Rhodamine 590 dye was pumped by this pulse train and subsequently frequency doubled using a single KdP crystal. Energies at the output were around 1 mJ per pulse near 282 nm.

1.3 The detection system

The detection system consisted of an ultra fast framing camera (Hadland). The camera featured 8 independent intensified CCD detectors with 8 bit dynamic resolution and 576 times 384 pixels. A special 8 facet pyramid beam splitter was used to relay individual imaged events to the respective CCDs. An optional, additional intensifier situated near the optical entrance to the camera increased its sensitivity to the level where it was capable of capturing single photon events. In this configuration, which was used for the present experiments, the camera had a maximum repetition rate of 1 MHz. A detailed discussion on the laser/camera system will be given [9].

1.4 OH *spectroscopy*

OH was excited using the $Q_1(8)$ transition near 282 nm in the $v'' = 0$, $v' = 1$ band of the $A\,^2\Sigma \leftarrow X\,^2\Pi^+$ system. Subsequent fluorescence in the (1, 1) and (0, 0) bands near 309 nm was observed using an interference filter (LaserOptik) and a UG11 filter. The laser beam was formed into a sheet 5 cm in height and 83 ± 15 μm in width in the interaction region. Laser pulse spectral densities at $5 \pm 2 \times 10^6$ $(\mathrm{W/cm^{-1}})\mathrm{cm^{-2}}$ were well below saturation levels for the indicated transition. The laser beam profile was monitored on line by simultaneously imaging fluorescence from a water solution containing fluorescing dye. Each image was normalised by this profile. The details of the set-up are very similar in nature to the ones described in [10].

2 Results and conclusions

Figure 1 shows typical results obtained from the flame. The Reynolds number $\mathrm{Re} = \rho v l/\mu$ (ρ = density, v = velocity difference, l = nozzle diameter, μ = viscosity) at the nozzle exit plane of the flame shown corresponded to around 5500. In the left pane a direct emission photograph of the flame is included to identify the regions imaged by the OH-PLIF displayed to the right. Each temporal OH sequence (labelled A to D in the figure) corresponds to an imaged height of 33 mm or about 7 inner nozzle diameters. The nozzle position is marked in the figure to the left of the lowest sequence. The time separation between successive images was 125 μs translating into an overall repetition rate of 8 kHz. At these repetition rates circulation of the dye in the dye laser was insufficiently fast to ensure that a fresh charge was available in the pump volume during time intervals between successive pulses. As a consequence, we observed a severe degradation in output intensity and laser spatial profile within individual pulse sequences. Related effects have been observed in double pulse pumping of dye lasers [6, 8]. A more detailed investigation of these phenomena is currently under way. In applications such as the present one laser beam profile referencing on a shot to shot basis is crucial for analysis of the PLIF images.

The transition from laminar to turbulent flow is clearly exhibited by the sequences. In region A of Fig. 1, close to the exit nozzle where flow is still laminar, the typical 'braids' of OH can be observed marking regions where fuel and oxidiser diffuse to, and mix in, the reaction zone. Local flame extinction is clearly seen in this sequence (highlighted by arrow 1). Most likely this is caused by convection building up strong local gradients which effect losses by molecular transport. This leads to a slowing down of chemical reactions to the point where the flame extinguishes. The sequence clearly highlights the capabilities of the technique: The temporal evolution of such events and possible re-ignition can be studied in real time. Based on the data shown, a convection velocity of $3.4 \pm 0.3\,\mathrm{ms^{-1}}$ is obtained for these unburned pockets thus corresponding to the fuel exit velocity.

Region B, starting about 10 inner nozzle diameters downstream, shows clearly the formation of vortices as a result of shear stress between the high velocity inner air flow ($\sim 21\,\mathrm{ms^{-1}}$) and the lower velocity fuel flow ($\sim 3.3\,\mathrm{ms^{-1}}$). Mixing rates are strongly enhanced by these eddies. One can clearly follow the progress of these vortices and gain information on the structural development of the flame. For a quantitative characterisation the turbulence intensity spectrum has to be measured as well, for example by laser Doppler anemometry or particle imaging velocimetry. For the purpose of the present demonstration this was not attempted but from the images it can be seen that the turbulence is not strongly developed since larger eddies are only just beginning to be formed in this moderate velocity flow system.

The flame is complicated by the fact that there is a further shear layer between the fuel and the surrounding (stagnant) air into which the flame is extending. Therefore there are two reaction zones on either side the fuel stream. Due to the low velocity difference, however, between the fuel flow and outer air, corresponding to $\mathrm{Re} = 400$ near the nozzle exit, the outer flame interface remains laminar across the entire distance imaged in region B, and indeed all regions shown. The broad zones marked by the OH-PLIF signals are indicative of the long lifetime of the species and diffusion effects, away from the primary reaction zones. Arrow 2 highlights a region where a broken flame reconnects and becomes continuous again. A similar event is pointed to by arrow 3 showing how this can lead to the formation of air pockets. Localised detached flame structures, can be seen (arrow 4). These are possibly flame islands but are more probably due to eddies originating from a region further back and cutting through the image plane. This ambiguity highlights the general limitation of 2 dimensional imaging techniques for the study of essentially 3 dimensional phenomena. The convection velocity of feature 4 is $24 \pm 1\,\mathrm{ms^{-1}}$ very close to the air exit velocity from the inner tube.

In region C a very broad distribution of OH is seen indicative of the long lifetime of the species which is mainly marking burnt gases here. Some unburned pockets (e.g. arrow 5) can be tracked in the central section of the flow which could be a consequence of an event such as highlighted by arrow 4, region B.

In the top section, region D, there is almost no change of the overall features over the time imaged. Most instabilities have been viscously dissipated and the images mainly show residual OH in the burnt gas and diffusive mixing with surrounding air.

In conclusion, we present here results from a novel laser/detector system which is ideally suited for the study of turbulence/chemistry interactions. Planar laser induced fluorescence imaging of OH at high repetition rates has been performed with excellent spatial resolution and good signal to noise ratio. Several phenomena which are characteristic for turbulent flames, such as extinction, entrainment, and pos-

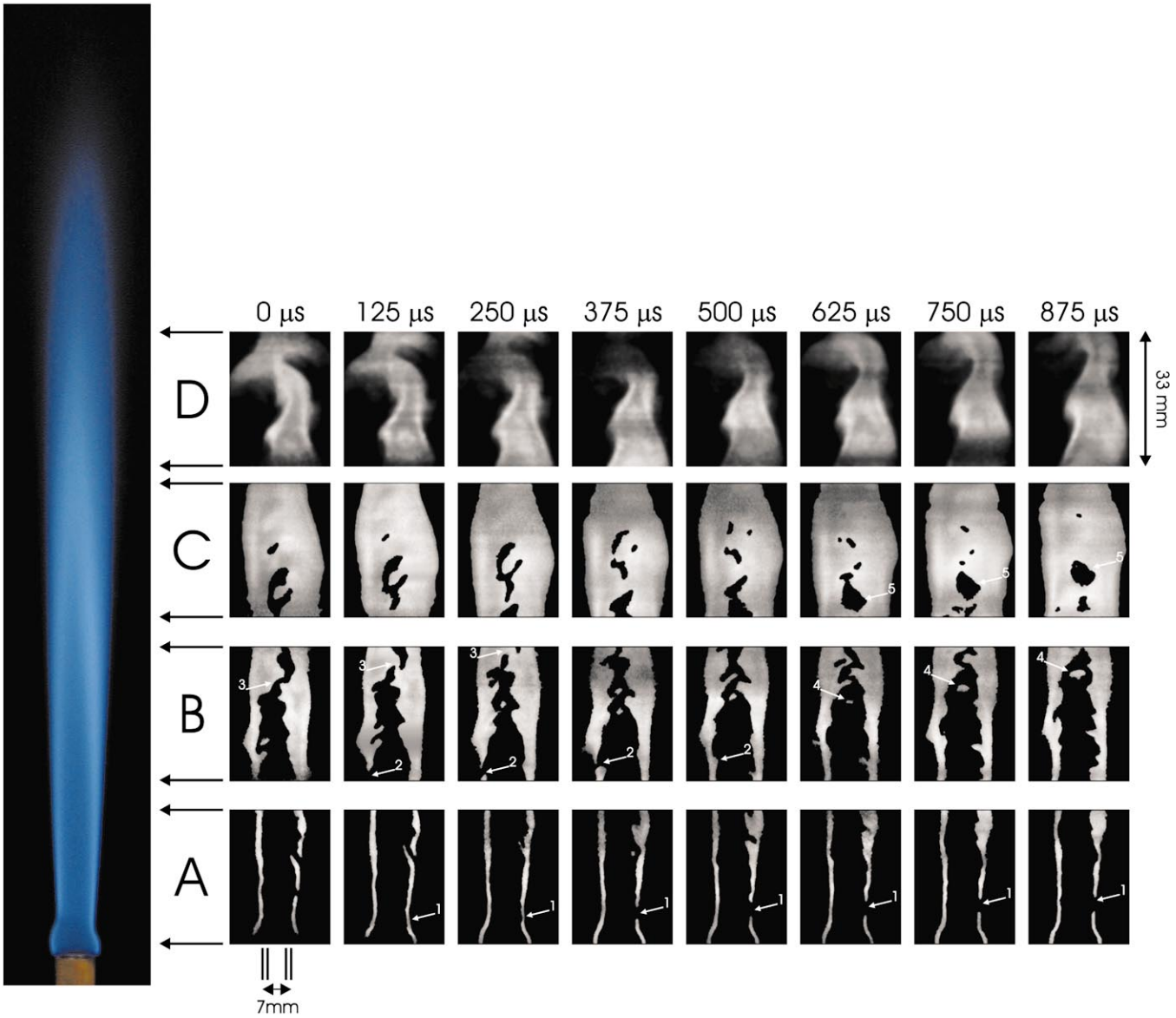

Fig. 1. Temporal PLIF sequences of OH at different heights in the turbulent, non-premixed CH_4/air-flame. A direct emission photograph of the flame is included to the left. Each PLIF-image shown corresponds to a single laser shot, time increases from left to right in 125 µs steps. The four measurement regions A, B, C, D correspond to the indicated positions in the flame

sibly flame detachment, could be captured and their evolution tracked in real time. The technique is non intrusive and does not require seeding of foreign particles into the flow. Furthermore, by studying a species which is produced in situ by reactions occurring in the flow one can obtain unique insight into the complex interrelationship between the physical and chemical phenomena occurring in reactive flows. At repetition rates up to 2 kHz the system has already been used for quantitative OH concentration measurements to characterise ignition events and monitor their evolution in real time [10]. Current efforts are directed at improving the dye laser system to be compatible with the high pump repetition rates required and to extend its operational range to a regime where the quantitative study of high Reynolds number flows can be accomplished. By rapidly sweeping the light sheet for successive pulses through the measurement volume the present technique is readily extended into a 3 dimensional volumetric rendering technique allowing three dimensional OH concentration measurements to be obtained.

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