Institute of Physics Publishing Journal of Physics: Conference Series **45** (2006) 19–26
doi:10.1088/1742-6596/45/1/003 Second International Conference on Optical and Laser Diagnostics (ICOLAD 2005)

PIV, high-speed PLIF and chemiluminescence imaging for near-spark-plug investigations in IC engines

C M Fajardo, J D Smith, V Sick

Department of Mechanical Engineering, The University of Michigan, Ann Arbor, MI, USA

vsick@umich.edu

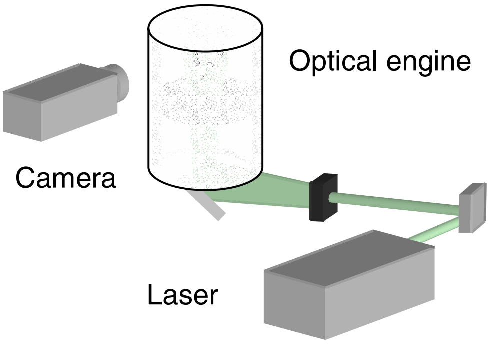
Abstract. Measurements of the local flow and mixture condition near the spark plug of internal combustion engines are important to characterize their influence on ignition and combustion performance. This is especially true for direct-injection engines where limited time is available for mixture formation and optimum stratification of the fuel/air mixture to achieve best performance. Transient processes need to be visualized in an optically challenging environment. The application of digital Particle Image Velocimetry (PIV) for flow field measurements along with crank angle-resolved planar laser induced fluorescence (PLIF) and chemiluminescence imaging is discussed in the context of investigations of a highly stratified spray-guided direct-injection engine. Flow fields were captured in a firing optical single-cylinder engine to study the interaction of the fast spray and the underlying in-cylinder tumble flow. The impingement of the fuel spray on the spark plug electrodes and subsequent dispersion of the fuel cloud was filmed at a rate of 12kHz with a new PLIF technique using a diode-pumped Nd:YAG laser. Subsequent flame development and combustion progress could be followed via high-speed imaging of OH^* chemiluminescence. This approach was also combined with double-pulse PLIF imaging of fuel distributions.

1. Introduction

The spark-ignition direct-injection (SIDI) engine provides an alternative to port fuel injected (PFI) engines, currently in widespread use [1]. Most of the advantages of SIDI engines rely on stratified charge operation, a mode suitable for part load (i.e. city driving conditions). Here, interactions of a high-momentum fuel spray plume and the spark plug promote a rich mixture near the spark plug, while the overall combustion chamber burns fuel-lean. As a result, it is possible to decrease fuel consumption and increase efficiency, while meeting the stringent emission standards of the near future. Achieving the fuel consumption and efficiency benefits of SIDI engines, which rely on optimized injection and burning strategies, are two important development goals. Attaining consistently reliable performance and acceptable pollutant emission levels are equally essential objectives. Both the equivalence ratio distribution and flow field characteristics near the spark plug near the time of ignition strongly influence the quality of individual burning cycles. For this reason, an understanding of their effects on ignition stability is of utmost importance in the SIDI engine development process. This paper describes several imaging techniques and their use in the investigation of spray-guided SIDI engine operation with a particular focus on near-spark-plug events.

2. Imaging of velocity, fuel distribution, and flame propagation

Particle Image Velocimetry (PIV), Planar Laser Induced Fluorescence (PLIF) and OH^* chemiluminescence experiments were conducted in a single-cylinder SIDI engine. Optical access is made possible by a quartz window placed in the extended (Bowditch) piston, as well as through the quartz cylinder liner and pent roof windows. More details of the engine are given by Fissenewert et al. [2] and Smith and Sick [3]. The generic setup, shown in figure 1, was used for all the experiments, while the hardware was appropriately selected for each case, as specified in the table given in figure 1 and subsequent sections.



	Laser, wavelength	Camera type (Image rate)
PIV	Dual Nd:YAG, 532 nm	CCD (4 Hz)
LIF	Diode-pumped Nd:YAG, 355 nm KrF excimer, 248 nm	intensified CMOS(12kHz)
OH^*	N/A	intensified CMOS(12kHz)

Figure 1 Schematic setup for PIV, LIF, and OH* chemiluminescence experiments. Relevant hardware specifications for each experiment are listed in the table on the right. Further description of the individual experimental setups is given in the following sections.

2.1. Optical engine operation

The single-cylinder engine was fueled with iso-octane for all experiments. For PLIF applications, different tracers were added as will be described below. Fuel was injected through an eight-hole injector with an end-of-injection timing of 40 crank angle degrees (CAD) before top dead center (BTDC). Ignition started at 34 °BTDC. The engine was operated in a skip-fired mode, one in three cycles fired for PIV experiments, and continuously fired otherwise. Optional intake air dilution with nitrogen to simulate exhaust gas re-circulation was available as well [3].

2.2. Particle Image Velocimetry

Laser Doppler Velocimetry (LDV) has been previously applied to obtain single and two-point measurements in premixed internal combustion engines [4, 5]. The development of PIV as a robust optical diagnostic technique allows the recording of instantaneous, two-dimensional, velocity field data from which relevant flow field quantities (e.g. strain rates and vorticity) can be calculated [6, 7]. These parameters can provide valuable information beyond the more traditional considerations of ensemble average velocities and RMS fluctuations. Two-dimensional velocity data have been obtained in motored SIDI [8] and fired PFI engines using PIV [9-11]. While the impact of the flow field on ignition and engine performance in spark ignition engines has been recognized, instantaneous, two-dimensional velocity data near the spark plug at the time of ignition in fired SIDI engines have been non existent until now. This can be attributed to the harsh environment that the experimentalist must overcome to obtain reliable velocity data under such conditions.

In this work, PIV was used to obtain velocity data around the spark plug near the time of ignition in a fired SIDI engine. The flow was seeded with 1 µm silicone oil droplets. A pair of frequency-doubled Nd:YAG lasers (New Wave Minilase) provided 13 mJ pulse each. Using a telescope arrangement, a 1 mm thick light sheet was created to illuminate the flow. An image pair was recorded per cycle every three cycles, on a 1376 x 1040 pixel CCD camera (FlowMaster Intense, LaVision). A bandpass filter

(532 nm) was attached to the camera lens to minimize interference. LaVision Davis 6.2 was used for synchronization and data processing.

Many experimental issues were anticipated to challenge the application of PIV near top dead center under firing conditions. The major noise contributions were expected to come from scatter off the piston surface, cylinder walls, and engine head, as well as from the spark luminosity. As a result of late injection, Mie scattering from the remaining spray droplets could overwhelm the signal from the seeding particles [12]. A sufficient dynamic velocity range was also needed to resolve flow and spray speeds. As top dead center is approached after the ignition event, a temperature rise above the droplet boiling point prevents maintaining homogeneous seeding, compromising the validity of the calculated velocity fields, and ultimately placing a limit on the number of crank angles after ignition over which reliable data can be acquired.

The bandpass filter was effective in minimizing signal contributions from the spark luminosity. The noise contribution from piston and cylinder surface scatter was greatly reduced by subtracting background images recorded prior to seeding the flow. The spray velocity, initially estimated at 20 m/s, was resolvable with the dynamic velocity range of the present setup. The limit on the maximum number of recorded images was not determined by optical access obstruction due to oil deposition on the cylinder walls, but was rather set by the maximum operating temperature of the quartz liner.

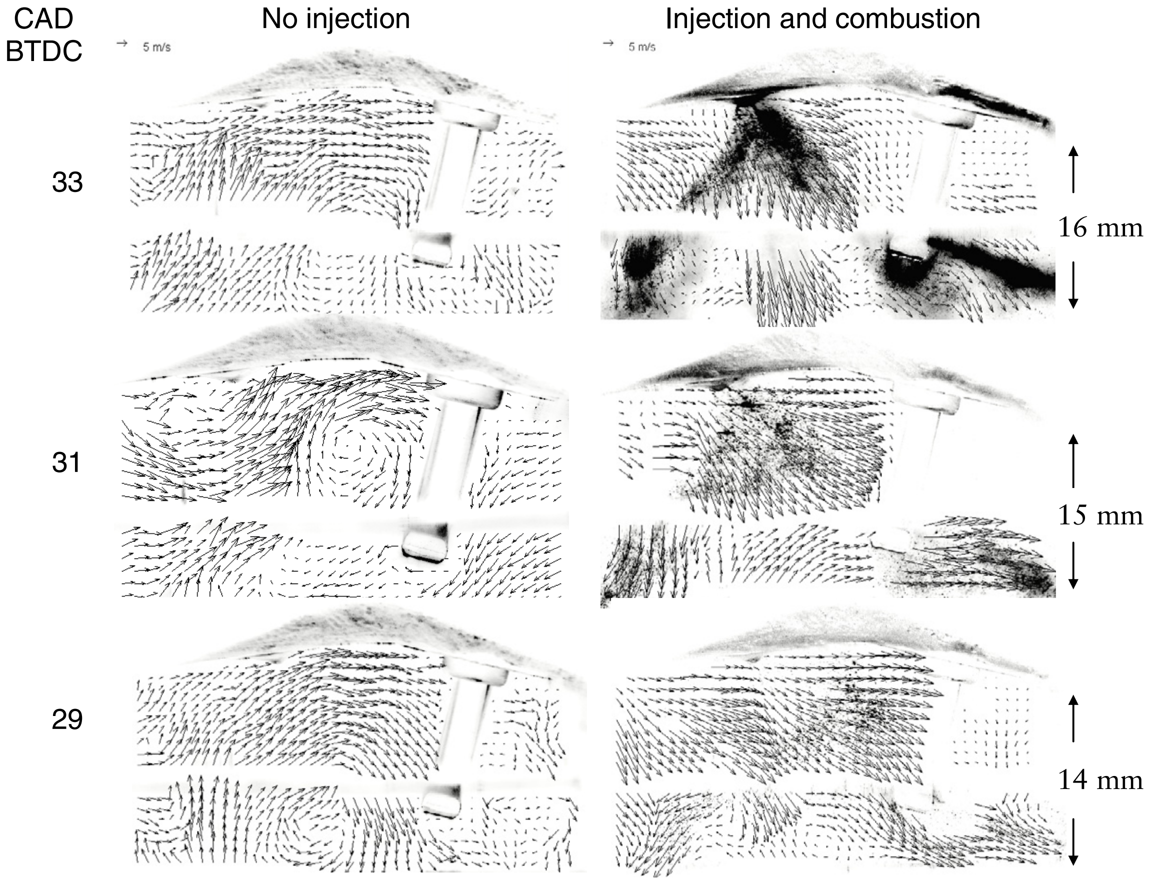


Figure 2 Instantaneous velocity fields obtained near TDC compression in a spray-guided SIDI engine. The left column shows images taken without fuel injection and ignition. The right column shows images recorded under firing conditions. End-of-injection is at 40 °BTDC and ignition starts at 34 °BTDC.

Examples of individual velocity fields at different crank angles are shown in figure 2. In each case, a set of fifty images was recorded while motoring the engine before activating the injection and ignition drivers to assess the seeding density and homogeneity level in the absence of effects from the spray residual and spark luminosity. During the same engine run, isooctane was then injected and the engine fired. Fifty images were recorded under firing conditions. Figure 2 shows results at 33, 31, and 29 °BTDC. Here, the flow fields have been superimposed onto the background to provide a geometric reference for the velocity fields. The white stripe dividing each image is due to the presence of grafoil linings between the quartz cylinder and cylinder head.

The left column in figure 2 shows instantaneous fields in the absence of ignition and combustion, whereas the right-column images, recorded under firing conditions, show how clockwise charge motion is disturbed by the residual spray momentum, especially at 33 °BTDC. Based on high-speed chemiluminescence data, the outlook for obtaining additional flow field information at later crank angles is promising. Further work will focus on separating spray and gas velocities and examining those flow field quantities relevant to combustion stability.

2.3. High-speed planar laser induced fluorescence imaging of biacetyl

Planar laser induced fluorescence imaging of fuel distributions in internal combustion engines has become one of the most widely used laser-based imaging techniques [13]. Typically, a non-fluorescing fuel is doped with a fluorescing tracer, e. g. 3-pentanone or toluene. Mostly, excitation is accomplished with KrF excimer lasers (248 nm) or frequency-quadrupled Nd:YAG lasers (266 nm). During the development of a high-speed version of fuel PLIF imaging, excitation at 355 nm from a frequency-tripled Nd:YAG laser was considered [14]. Excimer lasers are available with pulse repetition rates of ~ 2 kHz and pulse energies of 10-20 mJ. However, such systems are very large and costly. On the other hand, high-repetition rate Nd:YAG lasers are now available at moderate cost and size; however, pulse energies at 266 nm are in the µJ-range, which is not enough for imaging in engines. Therefore, absorption and fluorescence properties of biacetyl were investigated in more detail for its use as a fuel tracer in engines [15] using excitation at 355 nm. Biacetyl had been used in the past for engine experiments [16] but had not been further pursued as an alternative to other tracers.

The iso-octane fuel was doped with 10 vol.-% of biacetyl as a fluorescence tracer. The excitation source was a frequency tripled Nd:YAG laser (Quantronix Hawk) which produced nominal pulse energies of 0.41 mJ at 12 kHz. At this repetition rate, the pulse width is approximately 100 ns. The circular beam (approximate 0.6 mm diameter at outlet) was directed at a 45° mirror which reflects 355 nm light while transmitting 532 nm light (AR-coating on backside). After the mirror, the light was directed through sheet-forming optics (Rodenstock) to create a light sheet with a cross section of approximately 35 mm x 0.5 mm near the spark plug in the engine. The imaging system involves a high-speed CMOS camera (Vision Research Phantom V7.1) which is capable of capturing 4800 fps at full 800x600 pixel resolution. When an engine is running at 2000 RPM, the frame rate must be set to 12000 frames per second to achieve crank angle resolution. This reduces the image size to 386x386 pixels. The camera uses a memory gating function which allows for recording only during certain periods of the engine cycle. By utilizing this, the portions of the cycle that are of interest (e. g. injection, vaporization and combustion during the compression and early expansion stroke) can be recorded, while the remainder of the cycle is excluded. This allows for many more consecutive cycles to be recorded; generally 300 to 400 per experimental run.

To increase signal levels, a lens-coupled image intensifier (LaVision HS-IRO) was used. Fluorescence signals were focused onto the intensifier with a Nikkon 105 mm (f#=1.2) lens. The transmission of this lens decreases rapidly below 400 nm. A WG 385 filter (Schott) helped to efficiently suppress the recording of Mie scattering and scattered laser light from surfaces.

The image sequence shown in figure 3 was taken in the motored engine. The plume of one of the eight fuel jets is captured when hitting the spark plug electrodes to be split in two orthogonally propagating jets. Comparing the PLIF images with the velocity fields shown in figure 2, it is noticed that at 29 °BTDC almost all liquid droplets have evaporated and that the measured signal is predominantly due to gas phase biacetyl. Images were corrected for light sheet inhomogeneity but not for changes in absorption and fluorescence quantum yield. The strong fuel stratification that remains until very late is consistent with prior observations on flame propagation made with OH*-chemiluminescence imaging, see section below and [3].

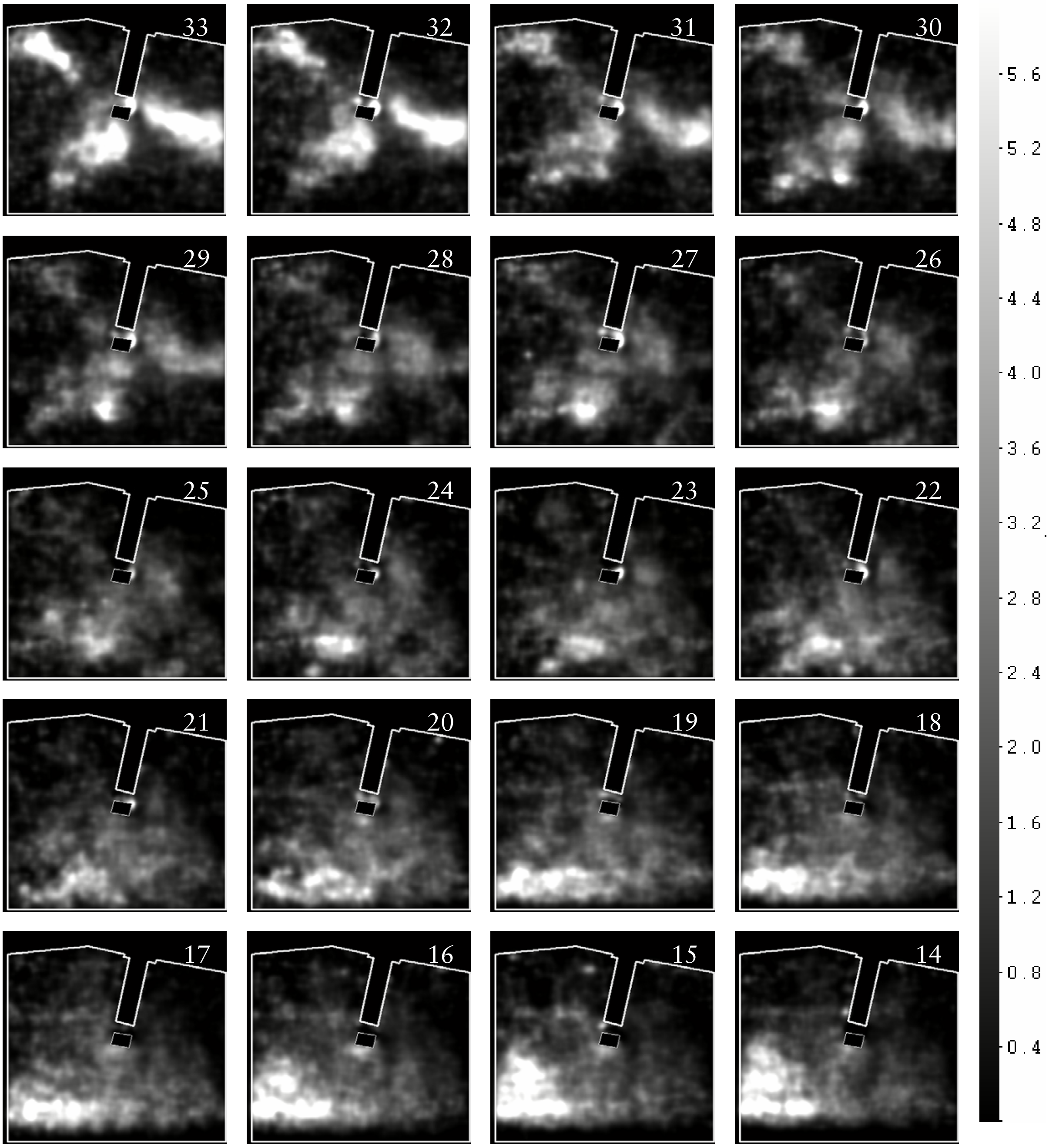


Figure 3 Biacetyl PLIF imaging sequence recorded at 12 kHz which equals 1 CAD resolution at 2000 RPM, in a motored spray-guided SIDI engine. The intensity scale (right) provides relative signal information. Numbers given in the images are CAD BTDC timing stamps.

2.4. Double-pulse planar laser induced fluorescence of toluene and high-speed imaging of OH^*

Especially when investigating cause and effect of ignition stability, it is desirable to obtain information about fuel concentration distribution, spark behavior, and flame initiation and propagation within individual cycles. This can be accomplished with a combination of PLIF of toluene and chemiluminescence imaging. Two KrF excimer lasers (Lambda Physik Compex 110, 248 nm) were synchronized to the engine crank angle encoder in such a manner that they fired with a time separation of 1 CAD. The laser repetition rate can be high enough to fire once every subsequent engine cycle. Thus, two fuel distribution images can be obtained per engine cycle.

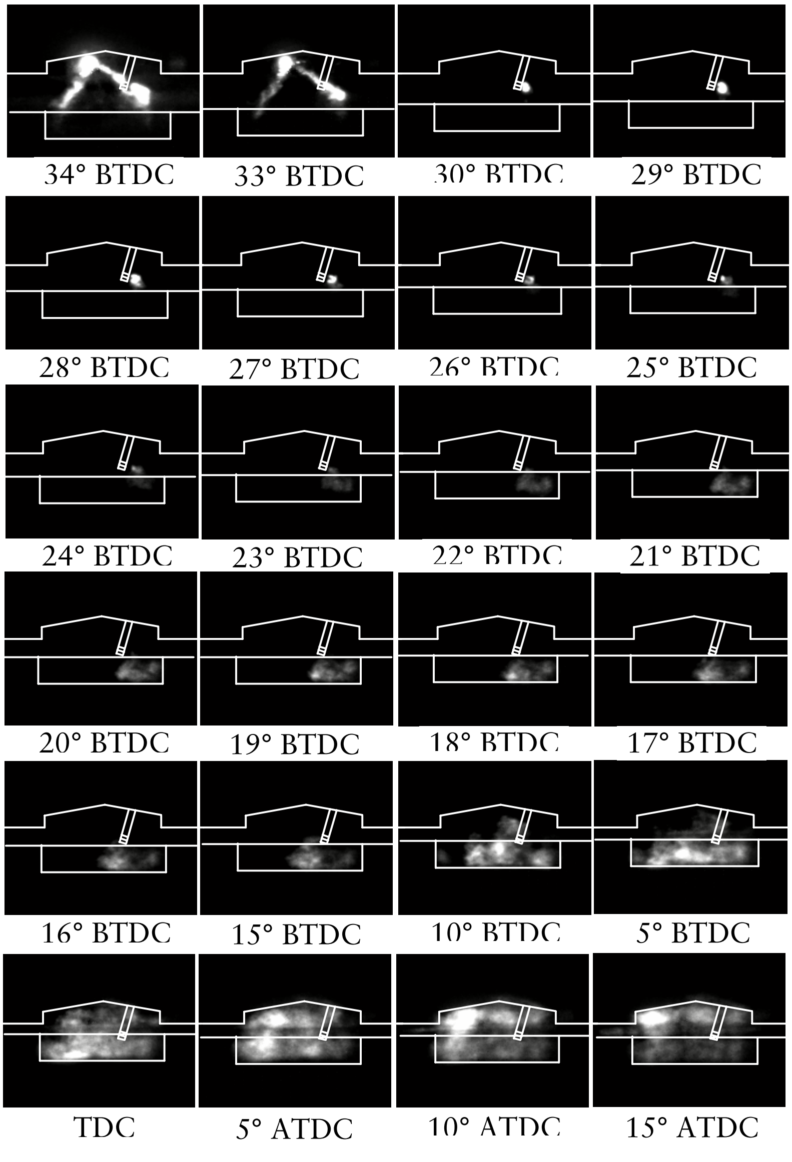


Figure 4 Combined imaging of PLIF of toluene (34 and 33 °BTDC), spark plasma emissions (30 -24 °BTDC), and OH* chemiluminescence (25 °BTDC – 15 °ATDC) allows crank angle resolved studies at 12 kHz frame rate.

The fluorescence signals of toluene were filtered with a narrow bandpass filter [17] centered around 300 nm. Signals were collected with a UV transparent lens (Halle, f=100 mm) and recorded with an image-intensified CMOS camera system (Vision research Phantom 7.1 and LaVision HS-IRO). The spark event itself can also be monitored with the same setup since the plasma emissions from the spark contain a band near 300 nm originating from OH radicals [18]. Lastly, flame initiation and propagation can be monitored well via OH^* chemiluminescence imaging at high image frame rates [19]. Again, the filter setup chosen for toluene fluorescence imaging accommodates the detection of these emissions as well. At camera frame rates of 12 kHz, one image per CAD can be recorded for several hundred consecutive cycles (see also section 2.2 for more details). Signal intensities of LIF and chemiluminescence can be adjusted via suitable selection of laser pulse energy and intensifier gate timing to match the dynamic range of the camera.

The image sequence shown in figure 4 illustrates the fuel distribution just prior to ignition followed by a long period (~ 10 CAD) of only emissions from the spark event before at 25 °BTDC the first indication of a growing flame is noticed. Note that in contrast to the example shown in the previous section, the fuel jet here is not split upon impingement on the spark electrode, illustrating the need for crank angle resolved imaging rather than phase-averaged scanning of engine cycles.

3. Conclusions

A brief overview was given on some imaging techniques that are useful for studies of in-cylinder mixing, ignition and combustion. Particular examples were discussed illustrating measurements in an optical single-cylinder spark-ignition engine that was operated in the spray-guided direct-injection regime. Particle image velocimetry was implemented to measure velocity fields around the spark plug in a firing engine. The use of a diode-pumped frequency-tripled Nd:YAG laser, in combination with a CMOS camera and high-speed image intensifier, allowed measurements of fuel distributions at rates of 12 kHz, corresponding to 1 CAD at 2000 RPM. Finally, the combination of imaging of LIF of toluene, plasma emission, and OH^* chemiluminescence with a single camera provides a useful tool for studies of cause and effect of cyclic variability on engine performance, such as power fluctuation or ignition instabilities.

4. Acknowledgements

This work was sponsored by General Motors Corporation through the General Motors-University of Michigan Collaborative Research Laboratory on Engine Systems Research. JDS is grateful to the College of Engineering for a Graduate Student Instructor appointment. The authors are also indebted to James F. Driscoll and Steven L. Ceccio at The University of Michigan for the loan of the Nd:YAG laser.

References

1. Zhao F, Lai M-C, Harrington D L. 1999 Automotive Spark-Ignited Direct-Injection Gasoline Engines. *Progress in Energy and Combustion Science*;**25**(5) 437-562.
2. Fissenewert U, Sick V, Pucher H. 2005 Characterization of combustion and NO formation in a spray-guided gasoline direct-injection engine using chemiluminescence imaging, NO-PLIF, and fast NO exhaust gas analysis. *SAE Paper 2005-01-2089.*
3. Smith J D, Sick V. 2005 High-Speed Fuel Tracer Fluorescence and OH Radical Chemiluminescence Imaging In a Spark-Ignition Direct-Injection Engine. *Applied Optics* accepted for publication.
4. Rask R B. 1979 Laser Doppler anemometer measurements in an internal combustion engine. *SAE Paper 790094.*
5. Arcoumanis C, Hull D R, Whitelaw J. 1997 Optimizing local charge stratification in a lean-burn spark ignition engine. *Proceedings of the Institution of Mechanical Engineers Part D-Journal of Automobile Engineering*;**211**(2) 145-154.
6. Raffel M, Willert C E, Kompenhans J. Particle Image Velocimetry: a practical guide. 1 ed. Berlin: Springer Verlag; 1998.
7. Reuss D L, Kuo T, Khalighi B, Haworth D, Rosalik M. 1995 Particle Image Velocimetry Measurements in a High-Swirl Engine Used for Evaluation of Computational Fluid

Dynamics Calculations. *SAE Technical Paper Series 952381.*

8. Richter M, Axelsson B, Alden M, Josefsson G. 1999 Investigation of the fuel distribution and the in-cylinder flow field in a stratified charge engine using laser techniques and comparison with CFD-modelling. *SAE Paper 1999-01-3540.*
9. Reuss D L, Rosalik M. PIV measurements during combustion in a reciprocating internal combustion engine. In: Laser Techniques Applied to Fluid Mechanics; 2000; Lisbon? 2000. p. 441-456.
10. Hildenbrand F, Schulz C, Sick V, Josefsson G, Magnusson I, Andersson Ö, et al. 1998 Laser spectroscopic investigation of flow fields and NO-formation in a realistic SI engine. *SAE Transactions*;**107**(Journal of Engines, Section 3) 205-214.
11. Josefsson G, Magnusson I, Hildenbrand F, Schulz C, Sick V. 1998 Multidimensional laser diagnostic and numerical analysis of NO formation in a gasoline engine. *Proc. Combust. Inst.*;**27** 2085-2092.
12. Driscoll K D, Sick V, Gray C. 2003 Simultaneous Air/Fuel-Phase PIV Measurements in a Dense Fuel Spray. *Exp. Fluids*;**35**(1) 112-115.
13. Schulz C, Sick V. 2005 Tracer-LIF Diagnostics: Quantitative Measurement of fuel concentration, temperature and fuel/air ratio in practical combustion systems. *Prog. Energy Combust. Science*;**31** 75-121.
14. Smith J D, Sick V. 2005 Crank-Angle Resolved Imaging of Biacetyl Laser-Induced Fluorescence in an Optical Internal Combustion Engine. *Applied Physics B*;**submitted**.
15. Wermuth N, Sick V. 2005 Absorption and fluorescence data of acetone, 3-pentanone, biacetyl, and toluene at engine-specific combinations of temperature and pressure. *SAE Paper 2005-01-2090.*
16. Baritaud T, Heinze T. 1992 Gasoline distribution measurements with PLIF in a SI engine. *SAE Paper 922355.*
17. Frieden D, Sick V. 2003 Investigation of the fuel injection, mixing and combustion processes in an SIDI engine using quasi-3D LIF imaging. *SAE Paper 2003-01-0068.*
18. Fansler T D, Drake M C, Stojkovic B D, Rosalik M E. 2002 Local Fuel Concentration, Ignition and Combustion in a Stratified Charge Spark Ignited Direct Injection Engine: Spectroscopic, Imaging and Pressure-Based Measurements. *International Journal of Engine Research*;**4**(2) 61-87.
19. Stojkovic B D, Fansler T D, Drake M C, Sick V. 2005 High-Speed Imaging of OH* and Soot Temperature and Concentration in a Stratified-Charge Direct-Injection Gasoline Engine. *Proc. Combust. Inst.*;**30** 2657 - 2665.