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THREE-DIMENSIONAL LASER INDUCED FLUORESCENCE OF FUEL DISTRIBUTIONS IN AN HCCI ENGINE

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Three-dimensional imaging of fuel tracer planar laser-induced fluorescence in a homogeneous charge compression ignition (HCCI) engine is presented. A high-speed multiple Nd:YAG laser and detection system, in combination with a scanning mirror, are used to collect eight images, with an equidistant separation of 0.5 mm. Three-dimensional isoconcentration surfaces calculated from the data are visualized. Three-dimensional imaging offers new opportunities to study different combustion events, specifically the topology of flame structures. For example, it is possible to distinguish if separate islands in a fluorescence image really are separate or if it is an effect from wrinkling in and out of the laser sheet. The PLIF images were also analyzed by identifying five intensity ranges corresponding to increasing degrees of reaction progress. The gradual fuel consumption and thus combustion was then analyzed by calculating the volumetric fraction of these intensity ranges for different crank angle positions. The occurrence of multiple isolated ignition spots and the observed gradual decrease in fuel concentration indicates that HCCI combustion relies on distributed reactions and not flame propagation.

Introduction

The combustion process is the most critical process that occurs in the internal combustion engine. The transformation of the chemically bound energy in the fuel into heat must be optimized. In order to increase the understanding of the basic properties of the combustion, optical diagnostic techniques have been applied [1]. These investigations have resulted in a more detailed knowledge of the combustion process in spark ignition (SI) engines as well as in diesel engines [2]. Optical measurements can be divided into three categories. The simplest is direct imaging, which is a line-of-sight integration of the total signal in the measurement volume, whereas laser sheet techniques provide information from a thin sheet cutting through the volume. These two types of techniques are complementary. If, for instance, the initial flame kernel size in a SI engine is to be measured, a line-of-sight technique can be a better choice than single laser sheet imaging. For example, it is possible to reconstruct the outer boundary extension by combining two simultaneous perpendicular line-of-sight measurements [3]. To investigate the structure of flame surface or the distribution of specific species, laser-imaging techniques are the only choice. However, the out-of-plane behavior cannot be resolved if only one laser sheet is used.

More information on the topology of the flame can be obtained with the third approach, where imaging techniques are extended to generate several simultaneous sheets, separated by a suitable distance. By combining the information from several two-dimensional sheets, a three-dimensional structure can be generated. This strategy has been used in turbulent laboratory flames and flows [4–7].

Cycle-resolved three-dimensional studies of the combustion process in engines have previously been limited to investigations of the turbulent flame propagation in an SI engine [8,9]. In this approach, a number of sheets of different wavelengths were generated and the Mie scattering from small particles, which where seeded in the inlet air, were collected. As the flame consumed the particles, a very distinct intensity difference was found between unburned and burned gas. This separation into only two zones, burned and unburned, is quite acceptable in an SI engine. In the SI engine, the reaction front separating the two regions is thin due to the short chemical timescale compared with the turbulent mixing timescale.

In homogeneous charge compression ignition (HCCI) engines, low emissions of nitric oxides (NO_x) and soot in combination with high efficiency has been demonstrated. In this type of engine, the homogeneous mixture is formed in the intake manifold. The mixture is then drawn into the cylinder during the intake stroke. At the end of the compression stroke, the temperature and pressure of the mixture exceeds the ignition point of the fuel. Autoignition occurs at many points almost simultaneously, where the local conditions are the most favourable, which means high fuel concentration and high temperature. The whole mixture is then consumed very quickly through distributed reactions, in about 1–2 ms. To avoid too fast combustion, lean or diluted mixtures must be used. The local combustion rate is low because the chemistry is slow, but the global combustion rate is high because a large part of the charge is involved in the combustion process at the time. For a thorough description of HCCI combustion, see Ref. [10], and for more information on chemical kinetics, see Ref. [11].

Since there will not only be the two zones of burned and unburned but also zones of intermediate fuel concentrations in an HCCI engine, Mie scattering is not a suitable technique in those environments. A more useful technique for visualizing the gradual fuel consumption is planar laser-induced fluorescence (PLIF) where a fluorescent tracer is added to the fuel. The detected signal is proportional to the concentration of fuel-tracer molecules. The combustion process in an HCCI engine has previously been studied using laser-based techniques, but these studies have been limited to line-of-sight techniques or to techniques using a single laser sheet [12–15].

This paper presents a technique to perform three-dimensional imaging of the fuel distribution using PLIF in an HCCI engine. A high-speed laser and detection system in combination with a scanning mirror was used for these experiments. Sequences of eight closely spaced images were recorded at different crank angle positions. From the eight images, three-dimensional isoconcentration surfaces were constructed. The relation between the size of structures in all three dimensions can be investigated from these data sets. To analyze the gradual fuel consumption, the LIF signal intensity was divided into five different intervals. The volumes corresponding to each of these intervals were calculated.

Experimental Approach

High-Speed Imaging System

To perform three-dimensional LIF measurements in turbulent combustion environments, a high-speed laser and detection system is necessary. The laser source is a cluster consisting of four individual pulsed Nd:YAG lasers. Each laser can be run in double-pulse mode, which means that the laser is fired twice during the flash-lamp pulse. The time separation between two such pulses ranges from 25 to 145 μs. By firing the individual lasers in series, a rapid burst of eight pulses can be obtained. A minimum separation of 6.25 μs can be obtained for equidistant pulses when the double pulses from the four lasers are overlapped in time. The overall repetition rate of the system is 10 Hz. In the beam-combining process, in which the laser beams are combined to one output beam, the fundamental 1064 nm beams are frequency doubled to 532 nm. To generate 266 nm radiation, which is used for the fuel visualization, an additional doubling crystal was used.

For detection, a modified high-speed framing camera was used. The camera consists of eight independent, intensified CCD detectors with 8-bit dynamic resolution and 576 $\times$ 384 pixels. A single optical input collects the signal, and an eight-facet beam splitter is used to relay the imaged events to the individual CCDs. The cameras are gated separately to detect a fast sequence of eight images. An additional intensifier was used in front of the camera to enable detection in the UV-region and to increase the sensitivity of the system. The maximum framing rate is 1 MHz when the intensifier is used. More details about the laser and camera system can be found in Ref. [16].

Test Engine

A Scania D12 single-cylinder engine, equipped with Bowditch-type optical access, was used in these experiments. The large window in the piston and the quartz cylinder liner allowed optical access to the major part of the combustion chamber. For the experiments presented here, the engine was operated at 1200 rpm with a compression ratio of 16:1. A lean fuel/air mixture, $\phi = 0.25$, was used. More detailed information about the engine can be found in Ref. [14].

Optical Setup

A three-dimensional image of the fuel distribution in an HCCI engine can be obtained by rapidly sweeping the laser beams through the combustion chamber, resulting in a small displacement between the laser sheets. The experimental setup is shown in Fig. 1. The eight laser beams from the Nd:YAG laser cluster, fired with 10 μs time separation, are spatially separated using a galvanometric scanning mirror. The scanning frequency of the mirror was 100 Hz. This results in a spatial separation of 0.5 mm between the individual laser sheets within the combustion chamber. All data was collected in 70 μs, corresponding to 0.5 crank angle degrees (CAD).

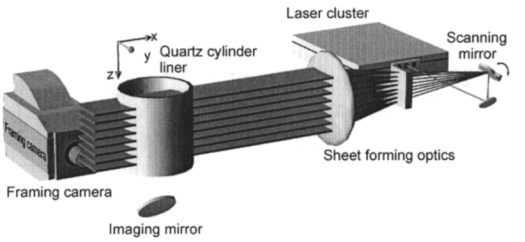

FIG. 1. Schematic overview of the experimental setup used for the three-dimensional visualization.

During this short acquisition time, the fuel consumption is nearly frozen. To verify this, images were recorded with same time separation and with all eight sheets at the same position in the engine. The cross section of the laser sheet was 50×0.25 mm^2. The sheet was formed by a cylindrical lens ($f = -100$ mm) and a spherical lens ($f = +1000$ mm). To achieve parallel laser sheets in the engine, the mirror was placed at the focal point of the spherical lens.

The fluorescence was detected, through the piston and via an UV-enhanced mirror placed in the piston extension, with an achromatic quarts lens (f/2, f = 100 mm). The camera was equipped with two different filters. One was a long-pass filter used to discriminate against scattered laser light at 266 nm while transmitting the LIF signal with a maximum at 430 nm. The other was a short-pass filter used to reject fluorescence at longer wavelength from oil residues on the cylinder windows and surfaces.

The depth of field of the imaging optics exceeded the dimensions of the measurement volume, which was $100 \times 40 \times 3.5$ mm^3.

Synchronization

The scanning mirror, the engine, and the laser-detection system were all synchronized. The engine speed was kept constant at 1200 rpm, corresponding to a combustion cycle frequency of 10 Hz. An engine trigger pulse, which corresponds to a specific crank angle position in each combustion cycle, was used to trigger a signal generator. The signal generator produced 10 sinus-shaped pulses with a period of 10 ms (100 Hz), which was used to control the scanning mirror. The pulse from the engine control system was also used to synchronize the laser cluster with the mirror.

Fuel Visualization

The measurements were conducted with PLIF. The fuel used in these measurements was ethanol. Due to the absence of fluorescence from the fuel itself, acetone, at a concentration of 10%, was added as tracer and works as a marker for unburned regions. The excitation wavelength was 266 nm, and fluorescence emitted in the spectral region between 350 and 550 nm, with a peak around 430 nm, was detected. The laser energy was approximately 25–30 mJ in each of the eight pulses. In this HCCI engine, the charge is completely evaporated and well mixed before ignition occurs. This makes the matching of the vaporization characteristics for the fuel and the tracer less critical. More important characteristics are that the tracer has suitable fluorescent properties and that it does not influence the combustion process itself [17–19].

Image Postprocessing

A number of image-processing steps have been applied to the acquired PLIF images. A background image, with no laser and combustion, was first subtracted from each image. To compensate for absorption along the path of the laser sheet, a mean absorption curve, which was extracted from an average eight-image sequence, was used. Inhomogeneties in the laser-intensity profiles were compensated for by dividing the individual images in a sequence, with an average laser profile. These profiles were extracted from unburned regions in the average sequence. The intensity of the eight individual images, constituting a three-dimensional image, were scaled to each other to compensate for remaining differences in laser intensity. To be able to compare the fuel concentration between three-dimensional images, completely unburned regions were set to the same intensity value in all three-dimensional images, and all the images were then scaled according to that.

To visualize the sequences as three-dimensional surfaces a shape-based interpolation scheme has been used. The first step in this procedure is to produce isoconcentration curves from the eight two-dimensional images by choosing a suitable threshold. Shape-based interpolation is then used to create new isoconcentration surfaces, in our case seven, between the original image planes. From these isoconcentration surfaces, a three-dimensional surface is constructed. For a more detailed description see Ref. [20].

Results and Discussion

Three-dimensional imaging has been performed at four different crank angle degrees, 2, 4, 5, and 6 after top dead center (TDC) corresponding to 22, 48, 61, and 69% of the accumulated heat release. For each measurement point, about 20 sequences of eight closely spaced images were recorded. Fig. 2 shows a typical measured cylinder pressure trace and the mean accumulated heat-release curves for each

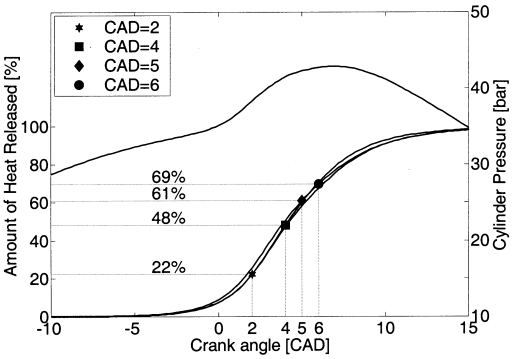

FIG. 2. Four accumulated heat-release curves for each of the four measurements points (2, 4, 5, and 6 CAD). A typical cylinder pressure trace is presented above the heat-release curves.

of the four measurement points. The heat-release data are calculated from the cylinder pressure measurements. Combustion is initiated by compression heat at about 5 CAD before TDC. As the consumption of the fuel continues, the cylinder pressure rises above the level it would have in absence of combustion. The pressure reaches maximum a few crank angles after TDC, but before the fuel is fully consumed, and then decreases during the remainder of the expansion stroke as the cylinder volume increases.

In Fig. 3a, eight equidistant fuel-tracer PLIF images recorded in the cylinder at 2 CAD after TDC are shown. The laser sheets cover a total volume of $100 \times 40 \times 3.5$ mm^3 in the cylinder, which corresponds to 35% (3.5 mm/10 mm) of the combustion chamber height. The field of view for the framing camera can be seen in Fig. 3c. In the images, the gradual consumption of fuel in the measurement volume can be seen. Burned regions, where the fuel is consumed, appear dark in the PLIF images, whereas unburned regions where fuel still is present appear bright. Regions where combustion is ongoing and where only part of the fuel has been consumed have intermediate intensities. The total three-dimensional acquisition time is 0.5 CAD; during this time, the combustion is considered to be nearly frozen. At 2 CAD after TDC, combustion has started, and in the volume shown in Fig. 3, about 40% of the fuel has been consumed.

The data from the LIF images were analyzed by identifying regions with a given intensity range. The engine was run at an equivalence ratio of 0.25, corresponding to 100% LIF signal intensity. The gradual fuel consumption and thus combustion was analyzed by extracting the volumes corresponding to >80%, 60%–80%, 40%–60%, 20%–40%, and <20% of the maximum signal intensity. This results in five discrete zones. An example of these zones, presented in different grey colors, is seen in Fig. 3b. The example shown is calculated for plane 5 in Fig. 3a. Three-dimensional isoconcentration surfaces,

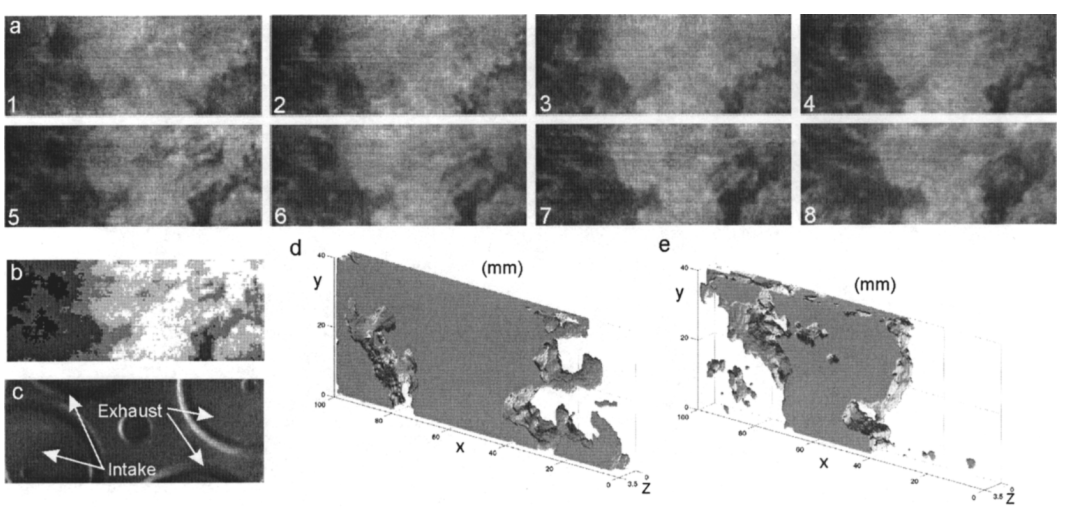

FIG. 3. (a) A three-dimensional fuel-tracer LIF sequence. Eight parallel and equidistant two-dimensional cuts of the fuel distribution in the engine are shown. The data were recorded at 2 CAD after TDC, when the engine was running at $\phi = 0.25$. (b) This image shows the fives different grey scales corresponding to LIF intensities of < 20%, 20%–40%, 40%–60%, 60%–80%, and > 80% of the maximum intensities in frame 5 in Fig. 3a. (c) Field of view for detection through the piston. (d) Three-dimensional fuel isoconcentration surface, corresponding to 50% of the maximum LIF intensity, calculated from the data presented in Fig. 3a. $z = 0$ at the first frame. (e) Three-dimensional fuel isoconcentration surface corresponding to 70% of the maximum LIF intensity.

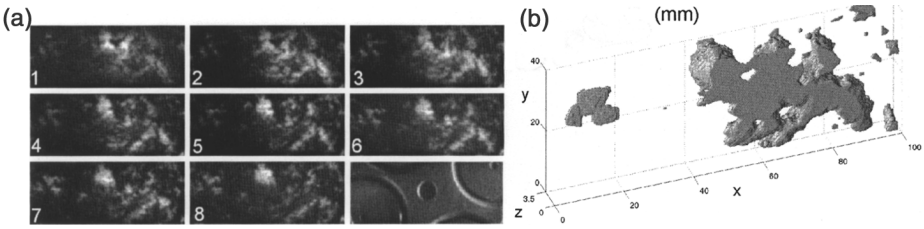

FIG. 4. (a) Three-dimensional fuel-tracer PLIF sequence recorded at 5 CAD after TDC. (b) The three-dimensional isoconcentration surface corresponding to 40% of the maximum fuel-tracer LIF signal.

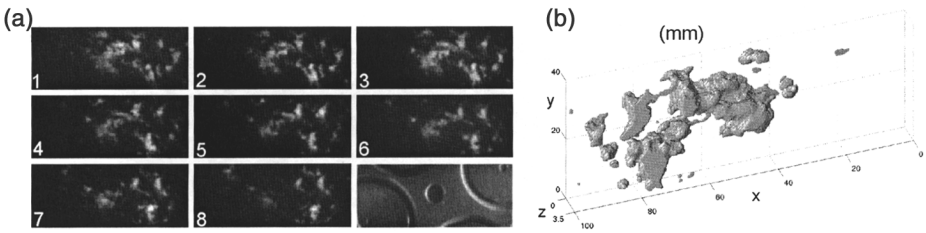

FIG. 5. (a) Three-dimensional fuel-tracer PLIF sequence recorded at 6 CAD after TDC. (b) The three-dimensional isoconcentration surface corresponding to 25% of the maximum fuel-tracer LIF signal.

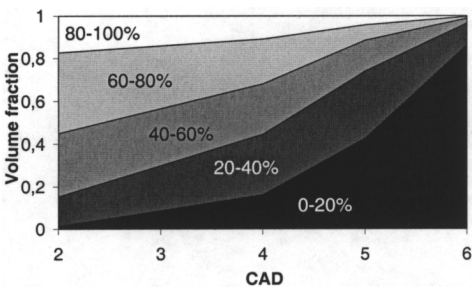

FIG. 6. The combustion progress illustrated by the average fuel concentration distribution in the three-dimensional measurement volume as a function of CAD after TDC. The distribution is calculated by separating the fuel tracer LIF signal into five intensity ranges.

corresponding to 50% and 70% of the maximum fuel-tracer LIF signal, have been calculated from the data shown in Fig. 3a. They are presented in Figs. 3d and 3e. The first frame in the sequence is recorded closest to the valves and is labeled $z = 0$ in the figures. The three-dimensional representations can be used to analyze the topology of the unburned fuel structures. For example, it is possible to distinguish if a structure that appears as an island in one of the two-dimensional images is a real separate island or a three-dimensional wrinkling effect in and out of the image plane. In the combustion cycle corresponding to Fig. 3, autoignition seems to have occurred at several positions in the cylinder, because two unconnected ignition kernels are clearly visible in the isosurface plots, one to the left and one to the right.

In Fig. 4, fuel PLIF data recorded at 5 CAD after TDC is shown, and the three-dimensional isoconcentration surface corresponding to 40% of the original LIF intensity is plotted. In the later part of the combustion phase more complex interfaces, as the one shown in Fig. 4b, between regions of high- and low-fuel concentrations are found. The isolated fuel islands found in the three-dimensional plot are caused by the multiple ignition kernels which finally merge. Fig. 5 corresponds to the later part of the combustion at 6 CAD after TDC. At this time, almost no regions with completely unburned mixture remains. Therefore, the 25% isosurface is displayed in this plot. This late in the combustion cycle, a large number of small isolated fuel structures are found in the cylinder and less than 10% of the fuel remains in the measurement volume.

Figure 6 shows the distribution of fuel concentration in the measurement volume separated in five intensity ranges as the combustion progresses. At 2 CAD after TDC, 22% of the heat is released according to Fig. 2. In this phase of the process, less than 20% of the volume contains the original fuel concentrations but almost no volume is entirely without remaining fuel. Two crank angle degrees later, 48% of the heat is released and this increases to 61% and 69% during the following two crank angles. In this part of the process, the 0%–20% zone grows rapidly. Approximately 30% of heat remains to be released at 6 CAD, even though more than 80% of the measurement volume contains very little

fuel. Thus, the heat-releasing reaction steps are not in full agreement with the decrease of fuel left in the cylinder and we can conclude that the chemical reactions producing heat must continue well after all original fuel is consumed. This is in contrast to the process in SI engines and clearly shows that the combustion in an HCCI engine is occurring through distributed reactions.

Conclusions

The present study reports on the first three-dimensional LIF measurements in an engine. The fuel distribution in eight closely spaced planes inside the combustion chamber of an HCCI engine was recorded. Statistical data sets of three-dimensional fuel distributions were collected for different crank angle positions. From the information in the eight LIF images, three-dimensional isoconcentration surfaces were constructed. From isoconcentration surfaces, the topology of fuel structures can be studied. For example, the existence of multiple unconnected flame kernels and also small isolated fuel islands were observed. In addition, all three spatial components of concentration gradients can be calculated from this type of three-dimensional data.

The recorded three-dimensional fuel distributions indicate that the HCCI combustion progresses as follows. In the early stage of combustion, most of the measurement volume was filled with unburned charge, corresponding to intensities above 80% of the maximum. Later in the combustion process, regions associated with an intermediate-signal range shows a maximum. At the end of combustion, there is a larger spatial spread of the remaining charge. Late in the combustion phase, some small islands generate high-signal intensity. This is interpreted as originating from more dense areas that are compressed by the expanding burned gases. The occurrence of multiple isolated ignition spots and the gradual decrease in LIF signal intensity could be detected with the three-dimensional measurement technique used. This does not only prove that HCCI combustion relies on distributed reactions and not flame propagation, but it also reveals the spatial structure of the oxidation process.

In the measurements in the HCCI engine, a time separation of 10 μs between consecutive laser pulses was used. In general, the timescales of turbulence and reactions of the measurement object determines the time separation between the laser pulses, which is required to freeze the combustion during the measurement. The smallest time separation that can be reached for an eight-pulse sequence with the multiple YAG system is 6.25 μs between each pulse. A more rapid pulse sequence can be fired consisting of only four pulses. Then the minimum of the time separation limitation is 1 μs, determined by the decay-time of the phosphors in the intensifier mounted in front of the framing camera.

The high repetition rates achievable allow the system to be used for three-dimensional imaging in different engine environments. The flexibility of the presented laser-detection system allows three-dimensional imaging of, for example, CH_20 or OH, as suitable wavelengths can be generated using third harmonic generation or tuneable dye lasers.

Acknowledgment

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REFERENCES

1. Wolfrum, J., *Proc. Combust. Inst.* 27:1 (1998).
2. Dec, J. E., SAE technical paper 97-0873.
3. Lindgren, F., Johansson, B., and Holst, J., SAE technical paper 97-2825.
4. Hult, J., Omrane, A., Nygren, J., Kaminski, C. F., Axelsson, B., Collin, R., Bengtsson, P.-E., and Aldén, M., *Exp. Fluids* 33:265 (2002).
5. Patrie, B. J., Seizman, J. M., and Hanson, R. K., *Opt. Eng.* 33:975 (1994).
6. Yip, B., Lam, J. K., Winter, M., and Long, M. B., *Science* 235:1209 (1987).
7. Island, T. C., Patrie, B. J., Mungal, M. G., and Hanson, R. K., *Exp. Fluids* 20:249 (1996).
8. Mantzaras, J., Felton, P. G., and Bracco, F. V., SAE technical paper 88-1635.
9. Hicks, R. A., Lawes, M., Sheppard, C. G. W., and Whitaker, B. J., SAE technical paper 94-1992.
10. Hultqvist, A., "Characterization of the Homogeneous Charge Compression Ignition Combustion Process," Ph.D. thesis, Lund Institute of Technology, Lund, Sweden, 2002.
11. Nilsson, D., Lovås, T., Amneus, P., and Mauss, F., *VDI-Ber.* 1492:511 (1999).
12. Christensen, M., and Johansson, B., SAE technical paper 98-2454.
13. Furutani, M., Ohta, Y., Kono, M., and Hasegawa, M., in *Proceedings of the Fourth International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines (COMODIA),* 1998, p. 173.
14. Hultqvist, A., Christensen, M., Johansson, B., Richter, M., Nygren, J., Hult, J., and Aldén, M., SAE technical paper 2002-01-0424.
15. Graf, N., Gronki, J., Schulz, C., Baritaud, T., Cherel, J., Duret, P., and Lavy, J., SAE technical paper 2001-01-1924.
16. Kaminski, C. F., Hult, J., and Aldén, M., *Appl. Phys. B* 68:757 (1999).

17. Neij, H., "Development of Laser-Induced Fluorescence for Precombustion Diagnostics in Spark-Ignition Engines," Ph.D. thesis, Lund Institute of Technology, Lund, Sweden, 1998.
18. Zhao, H., and Ladommatos, N., *Prog. Energy Combust. Sci.* 24:297 (1998).
19. Yip, B., Miller, M. F., Loranzo, A., and Hanson, R. K., *Exp. Fluids* 17:330 (1994).
20. Andersson, M., "Three-Dimensional Visualization of Turbulent Flames Using Shape-Based Interpolation," Master's thesis, Lund Institute of Technology, Lund, Sweden, 2000.

COMMENTS

Christof Schulz, Heidelberg University, Germany. The broad, distributed reaction zone with intermediate tracer-LIF intensities is in contradiction with what we found in other HCCI experiments using formaldehyde-LIF where very steep gradients in tracer concentration were found, allowing for unambiguous distinction between burned and unburned regions [1]. Could it be that the intermediate LIF intensities are due to partial destruction of the tracer?

REFERENCE

1. Gier, N., Gronki, J., Schulz, C., Baritaud, T., Cherel, J., Duret, P., and Levy, J., XAE paper 01:1924, 2001.

Author's Reply. In all experiments involving measurements on tracer species, it is important that the tracer follows and behaves like the molecules that are being marked. Based on the following arguments, the authors strongly believe that this is the case in the presented work.

As shown in Ref. [1], HCCI-combustion occurs through distributed reactions, with a gradual consumption of the fuel and thus, no flame front propagation. Ideally, the fuel tracer breaks up in a similar manner. That this is the case for the used fuel/tracer mixture is verified by simultaneously recorded fuel tracer FLIF and chemiluminescence images, where the areas of apparent chemiluminescence correspond well with areas of the decreased fuel concentration [2]. In addition, the correlation coefficient between the intensity of the chemiluminescence and the rate of heat release was found to be above 0.97 during the main heat release [3]. Together these two results indicate that the tracer species and the fuel molecules are consumed in a similar manner, both temporally and spatially.

REFERENCES

1. Onishi, S., Hong Jo, S., Shoda, K., Do Jo, P., and Kato, S., SAE technical paper 79–0501.
2. Hultqvist, A., Christensen, M., Johansson, B., Richter, M., Nygren, J., Hult, J., and Aldén, M., SAE technical paper 2002-01-0424.
3. Hultqvist, A., Christiansen, M., Johansson, B., Franke, A., Richter, M., and Aldén, M., SAE technical paper 1999-01-3680.