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Poster Contributions

Double Pulse 2D LIF as a Means for Following Flow and Chemistry Development in Turbulent Combustion

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A new approach for the measurement of turbulence time scales was developed based on double-pulse two-dimensional laser-induced fluorescence in combination with a correlation analysis. In a first application, the reaction zone of a turbulent H_2/air diffusion flame was studied with this method. For this, OH molecules were excited using two laser pulses which were delayed with respect to each other, but which pumped the same transition in the OH A-X (1,0) band. The laser-induced fluorescence of the same spatial region was detected using two gated CCD cameras. By varying the time delay between the laser pulses from 5 μs to 1 ms, the temporal changes of the OH-containing structures were determined. Spatial structures were also examined. Correlation analysis was used for a quantitative evaluation of the experimentally observed time and length scales for the regions where OH was present. The double-pulse 2D LIF method appears to be a promising tool for the investigation of turbulent flows. Its applicability is not limited to the example presented here. With the possibility to detect stable as well as radical species, it may provide a wealth of data on the temporal and spatial changes of a variety of scalars in both non-reacting and reacting turbulent flows which can be compared to mathematical turbulence models.

Introduction

Time scales of combusting and non-combusting turbulent flows are of importance in turbulence theory and combustion modelling, as well as in the characterization of turbulent flows. In addition, turbulent time and length scales must be known in order to choose a diagnostic method with an adequate temporal and spatial resolution for the investigation of the system of interest. Velocity measurements often are used in order to determine turbulent time scales, and several laser techniques have been established. However, most of these techniques (e.g., laser Doppler anemometry (LDA), particle image velocimetry (PIV) or laser speckle velocimetry) require a two-phase flow for velocity measurements, and thus addition of solid particles or droplets is needed if a pure gas flow is to be analyzed. This is especially disadvantageous if the system of interest is a reacting gas flow, e.g. a flame, because the particles might disturb the system, (in particular, heterogeneous reactions may occur) and the investigated system will not be the system of interest. LIF-based velocity measurements have been performed in order to avoid these problems [1 – 8]. These velocity measurements utilized either the Doppler shift of a molecular or atomic line or pulsed flow marking techniques using at least two lasers.

In the approach presented here, we decided to use LIF to detect a species which is already present in nearly all important combustion processes: the OH radical. Changes in structure or concentration can be determined by acquiring 2D LIF images at two different times and using a correlation-based approach to analyse turbulence time scales. Although this selection restricts the method to the regions of the flame where the OH concentration is high, we can ac-

quire information on the most important part of the flame: the flame front. Our double-pulse 2D LIF method can be used to measure time scales of turbulent combustion. It should be emphasized that the measured time scales are defined empirically and are not directly correlated to only one time scale of turbulent combustion, as e.g. the large-eddy-turnover-time or chemical time scales. The results of our measurements are a superposition of several of these time scales. However, models of turbulent combustion should be able to reproduce the measured features. The present data evaluation method is based on the cross-correlation of two time-delayed images. In principle, the method can be used to obtain a two dimensional distribution of time scales, as will be discussed in a following section. A similar approach was used by Yaney et al. [9], who used double pulse single point Raman scattering for measuring temporal scales.

In addition, spatial correlations of 2D OH distributions were also calculated. This approach might be advantageous for the quantification of two dimensional information and may assist in comparing experimental results to model calculations. Seitzman et al. [10] used auto-correlation analysis of total images in order to determine correlation scales and flame angles. In the present publication, only small regions in the images are correlated with neighbouring regions in order to determine correlations at specific locations with higher resolution.

One problem in the experimental determination of time scales is that turbulence time scales are typically defined as functions of quantities such as kinematic viscosities or turbulent Reynolds Numbers etc. which are difficult to determine experimentally [11]. Therefore, more empirically defined functions which describe the variation of correlation coefficients as a function of time or distance are used here.

Experimental Setup

Two frequency-doubled dye laser systems (Lumonics HD-500), one Nd:YAG (Quanta Ray DCR-2)-pumped and the other XeCl-excimer laser (Lambda Physik EMG 150 TSC)-pumped, were tuned to the $P_1(2)$ rotational line of the $A^2\Sigma(v'=1) \leftarrow X^2\Pi(v''=0)$ band of the OH molecule at 35377 cm^{-1}. The dye lasers were operated with Rhodamine 6G dye and Rhodamine 110 dye, delivering laser intensities of 6.4 and 1.4 mJ/pulse, respectively. Two laser sheets of 27 mm height and about 0.3 mm thickness were formed using $f = -70$ mm and $f = 400$ mm cylindrical lenses. The laser beams counterpropagated through the detection region of 6.7 cm with a small divergence which could be neglected.

The fluorescence which was induced by the two overlapping laser sheets was detected with $f = 105$ mm UV lenses (Nikon, UV-Nikkor) and focussed on two intensified CCD cameras (PCO, DICAM-2) aligned perpendicular to the laser beam direction. Both cameras were located on the same side of the laser beam and were very carefully aligned to record the fluorescence of the same spatial region. The total image area was 5.4 cm high and 6.7 cm wide, divided in 512×512 pixels. The image intensifiers were gated for 100 ns. No spectral filtering was used.

The laser pulse lengths of both lasers are less than 20 ns, so that the effective time resolution is better than 100 ns.

Using a multichannel pulse and delay generator (SRS DG535) the delay between the laser pulses could be adjusted accurately. The delay of the pulses was checked with an oscilloscope.

A turbulent hydrogen-air diffusion flame was investigated in this study. The burner was similar to the one described by Cheng et al. [12] and consisted of a 2 mm diameter nozzle. Pure hydrogen was flowed through the nozzle at 125 slm, resulting in a Reynolds number of 13900 at the nozzle exit. The visible shape of the flame is about 7 cm wide and 50 cm high. In the present study the laser sheet covered the height range between 2.5 and 5.2 cm distance from the burner exit.

Results and Data Evaluation

For several delays between 5 and 100 µs, series of 6–14 images pairs were recorded. In order to account for the spatial variation of the laser intensities, averaged laser sheet profiles were measured by detecting the fluorescence of a very dilute Coumarin 450 dye solution and correcting the corresponding OH images. Some small errors might arise from this procedure because the excited transition was partially saturated. Furthermore, the images were normalized to the same maximum value and the background level was subtracted. Laser pulse energies were not measured, but the normalization compensates for shot-to-shot total laser energy fluctuations.

The changes in the measured OH image pairs become obvious to the observer for delays larger than 100 µs (see Fig. 1). In order to quantify the similarity of an image pair, the cross correlation coefficients C of the image pairs were calculated according to Eq. (1) (see Ref. [13]). The correlation coefficient is a measure of the similarity of two images; its value is 1 for identical images, −1 for two images which are inversely correlated and 0 if the relation between the two images is arbitrary. $P(t=0)$ is the intensity distribution of the image which was recorded first and $P(t)$ is the delayed image. From each frame, the spatially averaged value of the pixel intensities (indicated by a bar) of the picture is subtracted. It is assumed that the pixel intensities are proportional to the OH concentration and temperature. As a first approximation, this assumption seems to be valid, because the quenching rates which can be calculated from the measurements of Meier et al. [14] vary by only 30% in the regions where OH is present. In addition, the quenching conditions should be very similar for the regions which are detected by corresponding pixels of camera 1 and camera 2.

$$C(t) = \frac{\sum_x \sum_y ((P(x,y,t=0) - \bar{P}(t=0))(P(x,y,t) - \bar{P}(t)))}{\sqrt{\sum_x \sum_y (P(x,y,t=0) - \bar{P}(t=0))^2 \sum_x \sum_y (P(x,y,t) - \bar{P}(t))^2}} \quad (1)$$

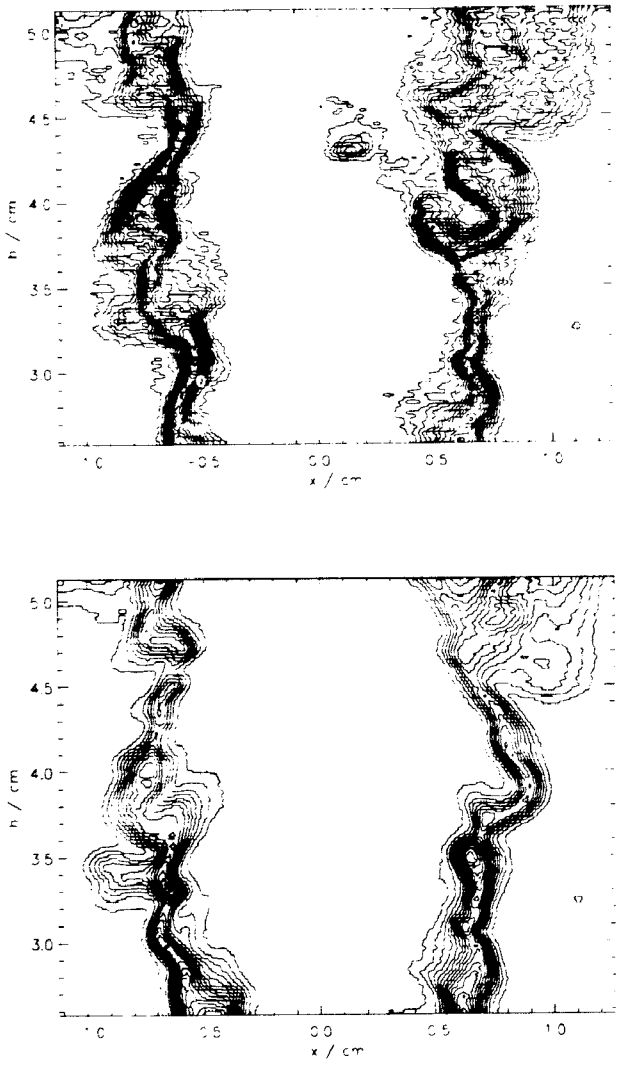

Fig. 1
Two typical 2D LIF single shot images. The lower image was recorded 100 µs after the upper one. Some changes in the structure can be recognized

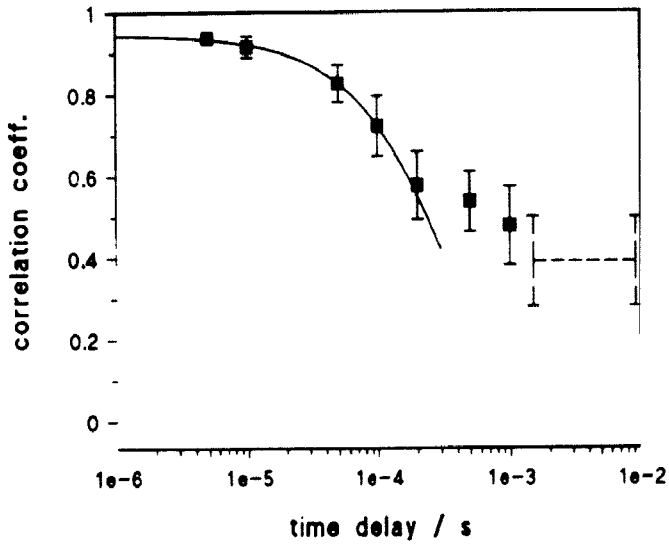

Fig. 2
The correlation coefficients as a function of time and the solid line is an exponential decay curve fitted to the points at small delays. The dashed line is the limiting value for long delays

The mean of the correlation coefficients of 6 to 14 image pairs and the according standard deviations of the central $2.9 \times 2\,cm^2$ are shown in Fig. 2. The height of 2 cm was chosen because the averaged laser energy profiles were constant within 30% in this region, so only minor normalization errors were made. Outside the selected width the LIF signal drops to zero. The mean value of the correlation coefficients of some arbitrarily chosen image pairs, recorded with delays between seconds and hours, are also included as a horizontal dashed line. The correlation coefficient of these image pairs does not converge to zero because the flame was not fully turbulent in the investigated region.

For the investigated flame region, the large OH structures have a decay time of 370 µs using a single exponential decay law which fits the data well for delays between 5 and 100 µs. The equation used by Yaney et al. [9] does not fit our data, because the correlation coefficients do not converge to zero.

Several processes can contribute to the changes in the OH structures. The most important seem to be chemical reactions and the structural changes of large eddies. In this flame region the latter should have time scales in the order of magnitude of several 100 µs (Cheng et al. [12]).

Horizontal and vertical spatial correlations were performed for a series of 50 images. From these correlations, information on the thickness of the flame front, as well as on the size of flow structures can be derived. As an example, two selected lines in an image were correlated with neighbouring lines in the same image. The coordinates and the length of the lines were chosen so that high signal intensities for at least a part of the line could be expected for each of the images. The calculations for the vertical correlations were performed according to Eq. (2); in the horizontal case, x and y in the equation have to be exchanged.

The definition of the variables is depicted in Fig. 3 and Δy is defined to be $y_1 - y_0$. For the vertical correlation, a horizontal line $(x_1 - x_0)$ of 1 cm length was chosen at the height, y_0 of 2.7 cm. Whereby the line of length $x_1 - x_0$ was shifted parallel

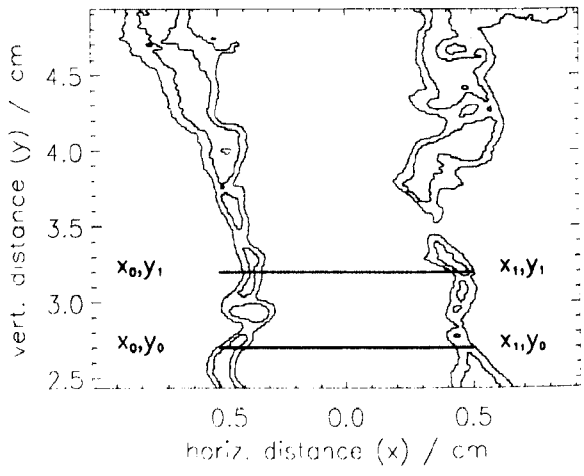

Fig. 3
The definition of the coordinates for the spatial correlation of two neighbouring lines, shown for the case of vertical correlation

$$C(\Delta y, x_0, x_1, y_0) = \frac{\sum_{x_0}^{x_1} ((P(x, y_0) - \bar{P})(P(x, \Delta y) - \bar{P}))}{\sqrt{\sum_{x_0}^{x_1} (P(x, y_0) - \bar{P})^2 \sum_{x_0}^{x_1} (P(x, \Delta y) - \bar{P})^2}} \quad (2)$$

to itself toward y_1. For 50 images the mean spatial correlations and standard deviations were calculated as a function of Δy and are shown in Fig. 4. For the horizontal correlation, a vertical line ($y_1 - y_0$) of 2.3 mm height was chosen at $y_0 = 2.6$ cm and a vertical distance $x_0 = 4.6$ mm from the center line. Now Δx was varied with constant x_0, y_0 and y_1. This correlation is also included in Fig. 4. Because of the small extension of the flame front in the x-direction, the horizontal correlation coefficients drop much faster to zero than the vertical ones.

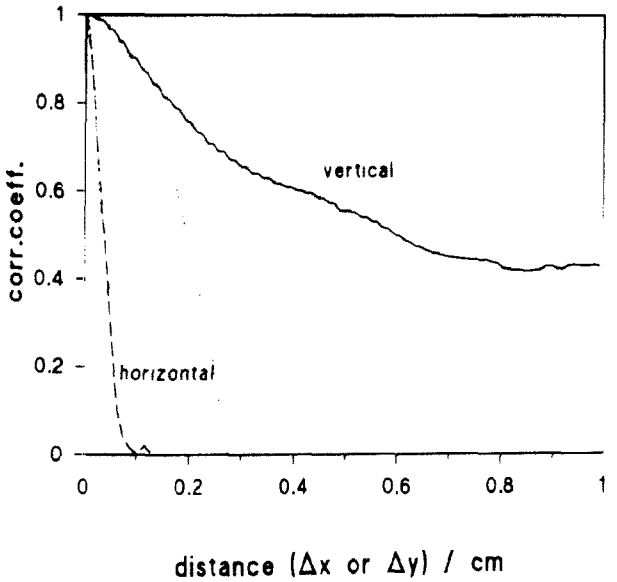

Fig. 4
The correlation coefficients as a function of vertical (solid line) or horizontal (dashed line) position, the dotted lines are fitted curves (for details see text)

In order to determine length scales the correlation coefficients for small displacements were fitted to following equation [15, 16].

$$C(x) = 1 - \left(\frac{x}{l}\right)^2 . \quad (3)$$

The resultant OH length scales in the vertical and horizontal directions are 0.28 cm and 0.04 cm. The first value should be a measure for the extent of flow structures, and the second value is indicative of the flame front thickness at measurements location.

Discussion and Conclusions

A new approach for the measurement of turbulent time scales was developed. In a first application, the reaction zone of a turbulent H_2/air diffusion flame was studied. The measured temporal changes of the OH signals can have several causes, e.g. fluid mechanical motions, chemical reactions as well as temperature changes and therefore the data are not easily interpreted, but models of turbulent combustion should provide such interpretations. The method is not restricted to the system presented here. For the comparison of the results of the double-pulse 2D LIF method with other methods for the determination of turbulence time scales, a simpler system would be preferred: e.g. a non-reacting cold turbulent flow doped with a tracer species, which can be detected by LIF. Such measurements are planned for the near future.

However, the application of temporally delayed double-pulse 2D LIF is a promising method for the experimental quantification of molecule-specific time scales of turbulent combustion. The measurement of empirically defined time scales of several different species should give more insight into the interaction of combustion chemistry and turbulence than the measurement of time scales which are defined by velocities. By using a larger statistical basis of at least 100 image pairs, time constants for each resolved pixel can also be determined and time scale maps can be plotted.

The spatial correlation curves might be very helpful in comparing two dimensional results with model calculations. If the flame which was investigated in the present study is studied with an increased spatial resolution of a factor of two to five, horizontal structures, which are indicative of the flame front thickness, could be resolved much better. With such a magnification, length scales in the order of magnitude of Kolmogorov scales of several turbulent systems should be resolvable. By using more stable tracer molecules, e.g. NO or acetone, non-combusting flows can also be analyzed, as long as concentration, temperature or density gradients are present.

In the near future, the variation of the time and length scales as a function of distance from the burner exit will be investigated. The whole time range from 50 ns to a few ms will be studied, and by recording at least 100 picture pairs per delay, time scale maps and length scale maps for different resolutions from single pixels to whole images will be determined. In addition, the same kind of measurements detecting seeded NO will be performed.

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Investigations on a Spark-Ignited Engine Using Two-Dimensional Laser-Induced Fluorescence

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Key Words: Flames / Fluorescence / Internal Combustion Engine / Knock / Spectroscopy, Ultraviolet

The method of laser-induced fluorescence (LIF) was applied to a modified industrial two-stroke engine with a single cylinder and spark ignition. Together, the disc-shaped combustion chamber and the low clearance height of the piston ensure mainly two-dimensional flame propagation. Formaldehyde is used as a natural tracer species for detecting and studying exothermic centres (so-called "hot spots") in the end gas. The latter contain a larger amount of formaldehyde than the enclosing end gas due to the slightly higher temperatures. To obtain two-dimensional excitation of the formaldehyde a laser light sheet enters from sideways through a ring-shaped quartz window. The fluorescence is detected via a full-size top window by means of an ultrashort-exposure ICCD-camera, and the frames are stored in a PC. Here, frames are presented which show 2D-LIF of formaldehyde in non-knocking as well as in knocking cycles.

Introduction

Engine knock is the major efficiency-limiting phenomenon in spark-ignited engines by causing severe damage to the surfaces of the combustion chamber. Generally, engine knock is considered to occur due to ignition of exothermic centres (so called "hot spots") in the end gas. Hot spots and autoignition, respectively, are considered to be produced by inhomogeneities in temperature at high pressure levels in the end gas [1]. Both the up-moving piston compressing the charge and the expanding burnt gas in the combustion chamber produce these high pressure levels.

During the first phase of a two-stage ignition a large amount of formaldehyde is formed in the unburnt gas. It is completely consumed during the second phase [2, 3]. Therefore, formaldehyde is one of the most important natural tracers of knocking combustion. However, the abundance of formaldehyde in the end gas region is used for detecting and studying exothermic centres by using a 2D laser-induced fluorescence (LIF) technique.

Experimental

The investigations were carried out in an engine especially adapted to the demands of 2D LIF-measurements. The complete set-up (Fig. 1) basically consists of three main parts, i.e., the laser system including the light sheet optics, the research engine, and the imaging system. The delay generator receives its trigger signal from the shaft encoder of the engine and then triggers both the laser system and the imaging system with their respective delays.

The laser system consists of an excimer and a dye laser. The latter is pumped by the excimer at 308 nm (XeCl). The employed dye, BMQ, is tunable from 335 nm to 375 nm and has its efficiency peak at 357 nm. The formaldehyde is ex-

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