Multi-Reaction Zones Imaging Technique for Turbulent Hydrocarbon Flames

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Abstract

Detection and imaging of multi-reaction zones is an essential tool for understanding the detailed structure of complicated flames. In this work a combined 4-camera technique is presented for multi-reaction zones imaging. The technique combines highly advanced laser-based diagnostics tools, namely Rayleigh scattering, laser-induced predissociation fluorescence (LIPF) of OH, LIF of PAH, and LIF of formaldehyde (CH_2O). The application of this combined technique in turbulent non-homogeneous hydrocarbon flames is quite new. The technique shows its ability to detect simultaneously rich, lean and diffusion reaction zones. The 3 reaction zones can be spatially resolved, providing essential information about their interaction and overall flame stability. Therefore, the detection and study of triple flame structures in non-homogeneous turbulent flames becomes possible. An example of a triple flame structure in a turbulent lifted non-premixed methane flame is presented. The present work proves that the developed technique is a powerful tool for multi-reaction zone measurements in turbulent and laminar flames.

Key words: Laser-based techniques, Triple flames, Multi-reaction zones, LIF, Formaldehyde.

Introduction

In many practical hydrocarbon combustion systems where the reactant mixture is not homogeneous, multi-reaction zones are expected. Numerical simulations of flame propagation in non-homogeneous mixtures (Domingo and Vervisch, 1996) show that triple flames and multi-reaction zones are likely to represent the main structure in this environment. Triple flames may also be called tribrachial or edge flames. They consist of 2 wings of lean and rich premixed reaction zones surrounding a diffusion flame (Phillips, 1965). The 3 reaction zones are usually attached at one end, called the triple point. An understanding of the structure and stability characteristics of these flames is essential for more efficient designs of combustion systems. The development of a quantitative measuring technique that resolves multi-reaction zones is the aim of this work. The main features of the target technique are high spatial and temporal resolution and the ability to separately resolve each reaction zone.

Several techniques (see Plessing et al., 1998; Watson et al., 1999, 2000; Santoro et al., 2000) have been applied in multi-reaction zone environments based on laser diagnostics tools. These techniques are based on monitoring relevant radicals in each reaction zone, e.g., CH and OH, in addition to Rayleigh and/or Raman for scalar measurements and planar imaging velocimetry for flow field measurements. Complete resolution of all reaction zones in turbulent flames was not possible due to the low concentration, and hence weak collected signal, of relevant radicals in lean reaction zones (Mansour, 2002). Recently, Mansour (2003) added another detector for

the lean reaction zone and was able to detect the triple flame structure in a partially premixed turbulent lifted flame. However, the signal was not strong enough for full coverage of all flames.

In this work, a combined laser-based diagnostics technique was developed for detection of all reaction zones in multi-reaction zone environments in addition to the mixture fraction. The technique combines Rayleigh scattering, laser-induced predissociation fluorescence (LIPF) of OH, laser induced fluorescence (LIF) of polyaromatic hydrocarbon (PAH), and LIF of formaldehyde (CH_2O). Each radical represents a reaction zone where OH is detected in the diffusion reaction zone while PAH and CH_2O are detected in the rich and lean reaction zones, respectively. The technique was tested in a turbulent lifted non-premixed methane flame where multi-reaction zones were expected.

Experimental Technique

The present imaging technique combines Rayleigh scattering for mixture fraction measurements, laser-induced predissociation fluorescence (LIPF) of OH radical for diffusion reaction zone detection, LIF of poly-aromatic hydrocarbon (PAH) for rich reaction zone detection, and LIF of formaldehyde (CH_2O) for lean reaction zone detection. The principles of those techniques are briefly discussed as follows. Rayleigh scattering is an elastic scattering signal, i.e. at the same wavelength of the laser, which is directly proportional to fuel mass fraction and inversely proportional to temperature (Mansour, 1993). In an isothermal mixture the Rayleigh signal can thus be used to measure the mixture fraction. The principles of Rayleigh scattering for mixture fraction or temperature measurements can be found in Dibble and Hollenbach (1981). Calibration of the Rayleigh signal in room air and pure fuel jet is sufficient for quantitative measurements of the mixture fraction in a non-reacting mixture.

The laser-induced fluorescence of OH radical technique has been applied in many turbulent flames and in practical systems to study flame fronts (Allen and Hanson, 1986; Felton et al., 1988). However, OH-LIF measurements require proper quenching correction for quantitative data reduction. Accordingly, Andresen et al. (1990) have developed another technique, called the laser-induced predissociation fluorescence (LIPF) technique, in order to eliminate the quenching effect. Laser-induced predissociation is

faster than LIF and thus energy loss, or the quenching effect, is not possible. The technique is quite simple to apply for the OH radical using a tunable KrF excimer laser operating between 248 and 249 nm. In the present work, the laser was tuned to P_2 (8) line to excite the $A^2\sigma \leftarrow (X)^2 \prod$ state, as reported in Andresen et al. (1988, 1990). A Schott UG11-glass filter was used in front of the OH-LIPF camera in order to select the OH-LIPF signal. Spectroscopic scanning was carried out for a stoichiometric methane-air flame to ensure that the signal was free from other interference occurring within the spectral range of the glass filter. The data were qualitative and used to identify the diffusion reaction zone.

In rich premixed Bunsen flames a laser-induced fluorescence signal of broadband PAH in the range of 400 to 600 nm has been tested and found to vary linearly with the laser energy. The signal is strong in rich flames and much weaker in lean flames (Plessing et al., 1998). Therefore, LIF-PAH was selected as a marker for the rich reaction zone.

For lean reaction zones neither OH nor PAH can be used as a marker. LIF of formaldehyde (CH_2O) has been successfully used by Santoro et al. (2000) as a marker for an edge flame, and by Bombach and Kappeli (1999) for detecting the flame front of a rich methane-air flame. Formaldehyde is usually formed at the early stage of hydrocarbon combustion, i.e. at low-temperature chemistry. In the present work, formaldehyde, CH_2O, was excited using the third harmonic of a Nd:YAG laser at 355 nm, similar to Harrington and Smyth (1993). At this wavelength the tail of the 4_0^1 transition in the $\tilde{A}^1A_2 \leftarrow \tilde{X}^1A_1$ band of CH_2O can be excited.

Based on the above principles a combined technique of 2 lasers and 4 cameras was built, as shown in Figure 1. The first laser was a tunable Kr-F excimer laser (Lambda Physik EMG 150 TMSC) at 248 nm with a narrow bandwidth of 0.001 nm and 250 mJ pulse energy. This laser was used for Rayleigh, LIPF of OH and LIF of PAH. The second laser was a Nd:YAG laser (spectra Physics GCR4) using its third harmonic line at 355 nm with about 0.03 nm line width and 300 mJ pulse energy. This laser was used for LIF of CH_2O at this wavelength, as explained above. The laser energies for both lasers were sufficient for single shot 2-D measurements. The 2 lasers and 4 cameras were synchronized and triggered using the Nd:YAG lamp output signal as the input trigger for the control unit. The excimer laser was triggered 1 μs after the Nd:YAG.
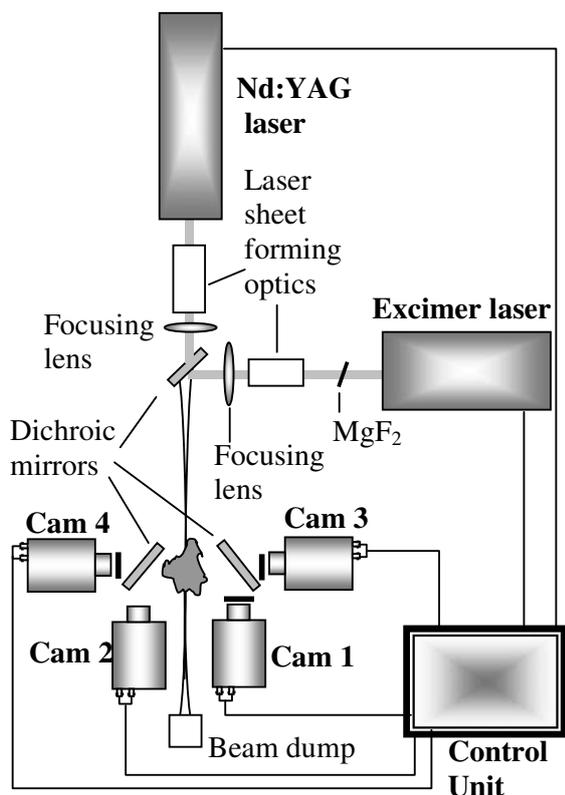
Figure 1. A schematic diagram of combined Rayleigh scattering, OH-LIPF, PAH-LIF and CH_2O-LIF technique.

Cam 1, shown in Figure 1, is an intensified CCD camera (Imager 3, 12 bit, Lavision 640 x 480 pixel array) that is used for imaging the OH-LIPF signal. Cam 2 is another intensified CCD camera (Sensi-Cam, 12 bit CCD array 640 x 480) that is used for imaging the Rayleigh signal. Cam 3 is another intensified camera (Dynamight 16 bit dynamic range, 512 x 512 pixel array) that is used for imaging the CH_2O-LIF signal. Cam 4 is similar to Cam 2 and is used for imaging the PAH-LIF signal. The gating time for all imaging intensifiers was set to 400 ns in order to suppress background reflections. One dichroic mirror is located in front of Cam 1 and Cam 3 at 45°. It reflects 298 nm to Cam 1 and transmits 350 to 700 nm to Cam 3. A UG11 filter is located in front of Cam 1 and a high pass filter at 400 nm in front of Cam 3. Another dichroic mirror is located in front of Cam 2 and Cam 4 at 45°. It reflects 248 nm to Cam 2 and transmits 355 to 600 nm to Cam 4. A high pass filter at 400 nm is used in front of Cam 4.

The 4 cameras were carefully aligned for matching. Therefore, direct correlation between pixel points in all CCDs could be achieved. This was tested over a stationary laminar Bunsen burner at several radial positions with an accuracy of ± 1 pixel. The spatial resolution for all cameras is 16.03 pix/mm and so the expected error in this matching procedure is within 62 μm.

Multi-reaction Zones Imaging in Turbulent Flames

The present combined technique was tested in a lifted turbulent methane flame. A jet of pure methane fuel was delivered at a velocity of 20 m/s with a Reynolds number of 4730 based on a cold jet. The flame was stabilized at a height of about 40 mm from a 4 mm diameter nozzle. The images were collected at the lift-off height covering an area of 31.94 x 29.94 mm for all cameras. This corresponds to a 512 x 480 pixel array.

Figure 2 shows a single 4-cameras shot collecting simultaneously 4 images of Rayleigh, CH_2O-LIF, PAH-LIF and OH-LIPF. Figure 2a shows the Rayleigh image where the signal is directly proportional to the fuel mass fraction, or mixture fraction, in the unreacted region. The image is illustrated in a false color rainbow-scale with blue representing the minimum signal in the hot products and red representing the maximum OH radical signal in the reactants side. The red contour in this image represents the flame boundary where the temperature is low. The fuel concentration has a maximum value at the centerline and decreases towards the outer sides. The weak signal is affected by both low fuel concentration and high product temperature. Therefore, no quantitative temperature or mixture fraction measurements could be extracted from these images. However, the flame boundary and mixture fraction through the unreacted mixture can be obtained.

Figure 2b shows a CH_2O-LIF image that represents the lean reaction zone at the outer edge of the flame and at the early flame front of low temperature chemistry towards the centerline. The signal is strong enough to identify the reaction zone contour of lean premixed flames. The CH_2O-LIF images have been corrected for methane Raman interference. The Rayleigh image is directly proportional to Raman and thus could be used for correction. Further correction due to OH interference was applied using the PAH-LIF image illustrated below. The image shown in Figure 2b was thus corrected for all possible interferences as explained above. The red

contour represents the locus of the maximum signal along the height. The lean reaction zone is clear at the outer sides of the flame. This is one of the main goals of the present technique that allows the detection of lean reaction zones in turbulent flames. This proves the existence of a lean reaction zone at the outer edge of turbulent lifted flames.

Figure 2c illustrates the PAH-LIF signal representing the rich reaction zone of the flame. The red contour represents the locus of the maximum signal as in Figure 2b. Figure 2d shows the OH-LIPF signal that represents the diffusion reaction zone with another red contour along its maximum OH-LIPF signal. The OH images were corrected for PAH interference using the PAH images.
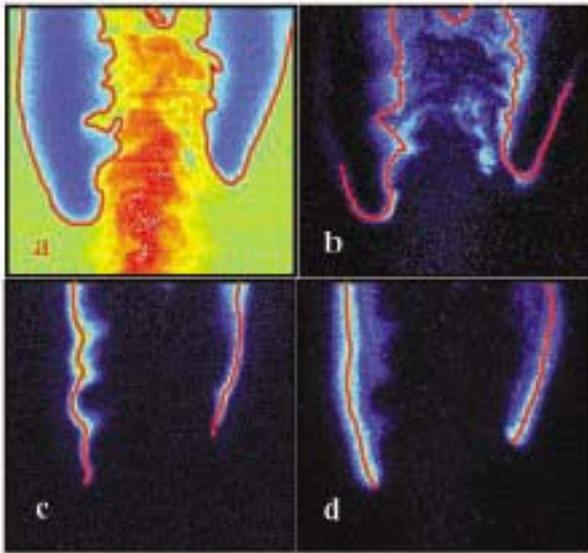

Figure 2. Simultaneous images of: (a) Rayleigh; (b) LIF-CH_2O; (c) LIF-PAH and (d) LIF-OH in a turbulent lifted methane flame.

Figure 2 shows 3 reaction zones in the present flame with high resolution. The images are matched together, as explained above, where the pixel locations in all are almost the same. For quantitative analysis of the collected data the red contours illustrated in Figure 2 are combined and presented in Figure 3. First the 3 reaction zones start with the rich one at the inside, followed by the diffusion and then lean reaction zones, as expected. It is also clear that the 3 reaction zones meet at a ring indicated by black dots. This meeting point between the 3 reaction zones can thus be called the triple point. In addition, the Rayleigh signal, representing the flame boundary, and the CH_2O-LIF signal for low temperature chemistry follow quite similar profiles. The

same analyses were applied for averages of 100 shots leading to average contours of the 3 reaction zones and Rayleigh. Then the average 4 contours were extracted and are combined in Figure 4. Similar trends can also be observed with a triple ring at the flame base representing the attachment of the 3 reaction zones. This proves the reliability of the present technique for extracting simultaneous reaction zones profiles on a single shot and average basis. The present technique can thus provide quantitative data describing multi-reaction zones and triple flames in a turbulent reacting non-homogeneous combustion medium. More data are presented in Joedicke et al. (2005) for different flames at different turbulence levels where the triple flame structure could be captured.
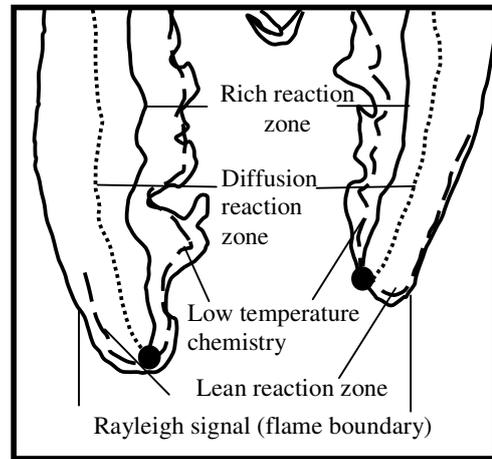

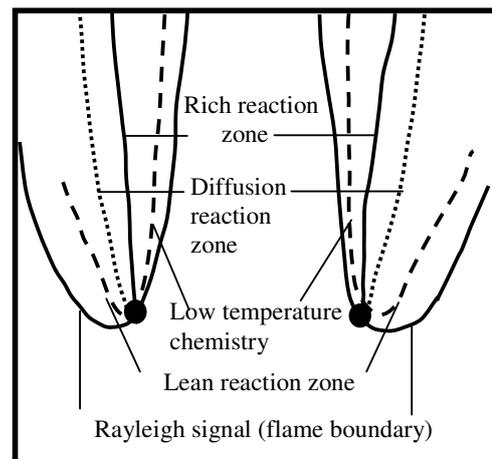**Figure 3.** Combination of the red contours illustrated in Figure 2. The black dots represent the triple points.

Figure 4. Similar contours to those presented in Figure 3, but extracted from the average images.

Conclusions

A combined laser-based technique was developed and applied in the present work for resolving a multi-reaction zones structure in a non-homogeneous turbulent combustion medium. The technique combines Rayleigh scattering, LIPF-OH, LIF-PAH and LIF-CH_2O using 2 lasers and 4 cameras. It was tested successfully in turbulent lifted non-premixed methane flame and proved its ability to resolve simultaneously lean, rich and diffusion reaction zones. The triple flame structure was completely resolved with its triple point. The application of this technique in a turbulent non-homogeneous combustion environment should solve many of the problems related to the understanding of flame stability and local structure. It is thus considered a powerful imaging tool for many practical and fundamental combustion systems.

Acknowledgments

Nomenclature

LIPF Laser induced predissociation fluorescence
LIF-PAH Laser induced fluorescence of polyaromatic hydrocarbon (PAH)

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