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A Review of Recent Advancement in Combustion Diagnostics.

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Abstract : It is well known that combustion environment happens to be very hostile for measurements. The conventional techniques used until recent were in many situations, inadequate and restrictive to the progress in experimental investigations in combustion even as the computational studies made rapid progress. However in the past one decade or so, the advances in diagnostics especially in the laser based non intrusive diagnostics have given a fresh impetus to experimental studies. Indeed most of the recent reports deal more with probing with the new diagnostic tools than with newer experimental configurations. The present article gives a glimpse of some of the recent diagnostics technique and those newly adopted for combustion studies which have pushed the frontiers of our knowledge of combustion.

Keywords **- LDV Measurement,PIV Technique, LIF, Combustion.**

I. INTRODUCTION

Combustion as a technology has a history of several centuries but a rigorous scientific study has perhaps been made only in the last hundred and fifty years, particularly in the last fifty years. Until 1970's analyses with techniques such as asymptotics and to some extent with numerical solutions were the mainstay of theoretical combustion research matched by equally simple experimental diagnostics such as thermocouple measurement of temperature, off line gas analysis and cine photographic/schlieren measurement and so on. Then there was an explosive growth in computational capabilities and in a relative sense the experimental techniques appeared to lag behind considerably. In the last ten to fifteen years, there has been a resurgence
in the experimental activities thanks to the new diagnostics tools, especially the laser based non intrusive techniques [1-4]. In a way the computer based scanning, data acquisition and data reduction have charted a new course for experimental studies. There has also been increasing need to validate the mathematical models and the numerical solutions by finer and more refined experimental data. The state of art combustion research is elevated to new height now as both computational and experimental tools have become very sophisticated. Majority of the new diagnostic tools work with lasers and indeed are extensions of known
spectroscopic techniques or computer based image processing techniques. Interestingly as new diagnostic methods become available, the older combustion problems are often revisited and refined data are generated. In the process, one rarely comes across new combustion configurations which may add to our understanding.
Flames and combustion systems vary widely in size, fuel type and purpose. Also wide variations in pressures, temperatures and flow patterns are present depending upon the combustion system. The state of any reacting gas mixture at one spatial location is described completely when the velocity, temperature, pressure, density and the mole fractions or mass fractions are known. Further, when condensed species are present, such as fuel particles or soot, one need to describe their sizes, distribution and motion. The limits placed by the combustion environment on the diagnostic instruments to follow these parameters include space and time resolution, detectives and dynamic range. They are determined by the nature of the particular flow process encountered and by the chemical kinetics involved. Excellent techniques with high
spatial and temporal resolutions, mainly non intrusive optical techniques that replace conventional sampling methods have evolved in the recent times. A complete review on this topic is well beyond the scope of this paper. However a few diagnostic techniques of importance in the realm of combustion have been picked up and explained with principles and recent applications.

Laser Doppler Velocimetry (LDV)

Laser Doppler Anemometry (LDA) or Laser Doppler Velocimtery (LDV) is an optical system used to measure fluid velocities under complex flow environments. Some of the present features of this technique which was invented in 1964 are (1) it is non intrusive (2) it requires no calibration (3) it covers a velocity range from zero to supersonic (4) simultaneous measurement
of one, two or three velocity components is possible (4) measurement distance can vary from centimeters to meters (5) flow reversals can be measured and (5) it provides high spatial and temporal resolution In LDA technique particles are added to the flow. The flow velocity information comes from light scattered by these tiny seeding particles carried in the fluid as they move through the measurement volume. As with all particle scattering of light, conservation of momentum leads to Doppler effect, a slight shift of frequency of the scattered light in proportion to its velocity. As the particle traverse through the fringe pattern in the measurement

volume (Figure 1), dark and bright bands obtained by the intersection of two coherent laser beams, the scattered light fluctuates in intensity with a frequency equal to the velocity of the particles divided by the fringe spacing. The fringe spacing is defined by the wavelength of the laser light and the angle between the beams. The scattered light passes back through a lens and a receiving fiber onto a detector (a photodiode or photomultiplier). The photo-detector converts the fluctuating light intensity to an electrical signal, the Doppler burst, which is sinusoidal with a Gaussian envelope due to the intensity profile of the laser beams. The Doppler bursts are filtered and amplified in the signal processor, which determines the Doppler frequency, fD for each particle, often by frequency analysis using the robust Fast Fourier Transform (FFT) algorithm. The fringe spacing, df provides information about the distance traveled by the particle. Knowing the fringe spacing and the frequency the velocity is obtained as v=df*fd. The other velocity components are found by forming fringes orthogonal to the first set. Two orthogonal fringe sets can be formed by passing four beams through a single converging lens. Signal separation for each fringe can be
accomplished by using laser light of different colours. A typical experimental measurement obtained from LDV is shown in Figure 1. Preparation of scattering medium is important in LDV. Liquids often contain sufficient natural seeding, whereas gases must be seeded in most cases. Ideally, the particles should be small enough to follow the flow, yet large enough to scatter sufficient light to obtain a good signal-tonoise ratio at the photo-detector output. One micro meter diameter particles have proven to be satisfactory compromise for subsonic flows.

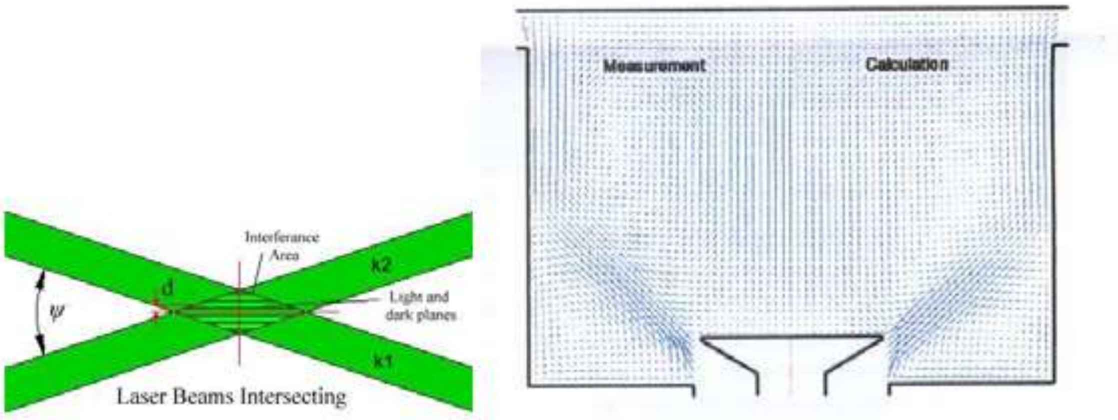

Figure 1. Fringe pattern and a typical application of LDV result

Besides exploring velocity profiles LDV has also been used to measure the particle sizes. Using the concept of a visibility term which defines the maximum and minimum intensities in the pattern of light scattered by the particle and the fringe pattern from LDA, the size of a spherical and non spherical particle can be determined [5]. Fuel droplet sizes along with velocities in combustion zones have been measured successfully using LDV [6].

Particle Image Velocimetry (PIV)

Particle imaging velocimetry is another useful technique to measure velocities in fluid flow fields. PIV is an optical technique which captures images of illuminated particles within the flow field. It estimates the fluid flow velocity vectors at several points in the selected region simultaneously. The particle velocity is calculated from the distance the particle moves between two pulses of a light source. The period of time the beam is on and the time the beam is off is the separation time between pulses. The range of times can be varied to cope with a variety of velocity or brightness requirements. Since the flow can be fast one need to use laser pulses. The images are captured by a CCD camera perpendicular to the light sheet. The CCD camera and optics may be mounted on traverses to scan different areas of the flow field. These images are analyzed digitally to obtain 2D velocity field frozen in time. Figure 2 shows the basic principle of PIV.

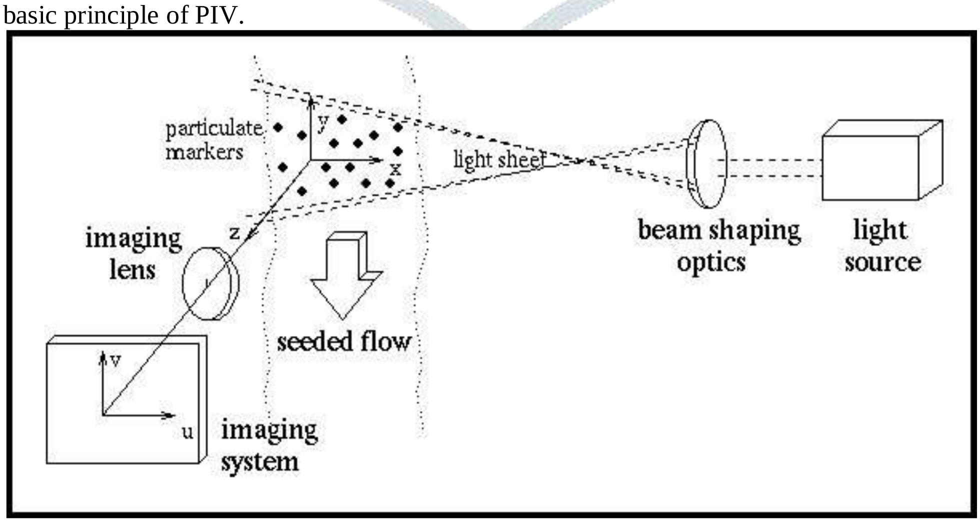

Figure 2. Schematic of a PIV technique

Resolution of the image for processing depends on the camera's resolution and the size of the flow field area being scanned. The accuracy of the PIV data is a function of the image resolution and the timing of the pulse separation. Different techniques are employed for processing the PIV images such as particle pairing, autocorrelation and cross correlation.

Many more advancements have been made in PIV measurements. A 3D-Stereo PIV is based on the principle of stereoscopic imaging: two cameras capture the image of the illuminated particles from different angles. Figure 3 shows the flow velocity of a 3D swirling airflow.

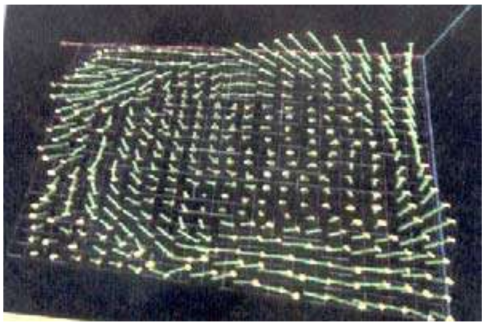

Figure 3. Steroscopic PIV measurement: Swirling air flow

PIV measurements in IC engines, turbo machinery or pumps usually require the manufacturing of expensive prototypes with large glass windows. Development of Endoscopic PIV wherein endoscopes are utilized for the camera and the laser has been reported recently. Small optical access (8 mm hole) enables the PIV measurements to be made easily without building costly prototypes with large windows for optical access. Figures 4 and 5 show results of endoscopic and standard PIV measurements made in the central cross section of an SI IC engine [7]. Development of a micro PIV System to measure velocity fields of particle seeded flows with micron scale spatial resolution is another advancement in the area of PIV techniques.

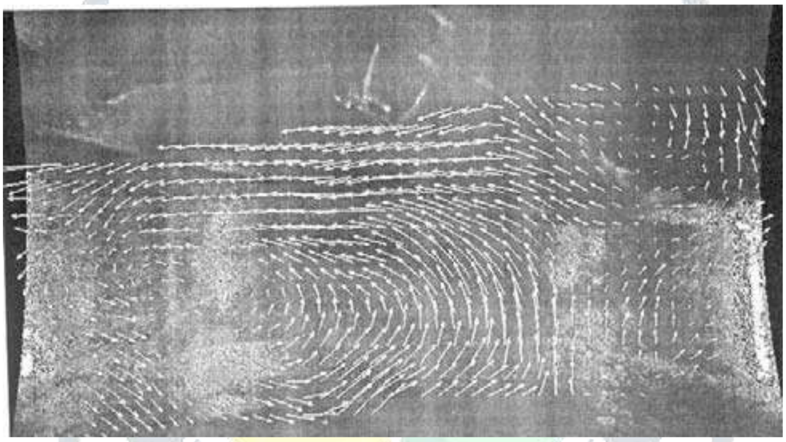

Figure 4. In cylinder tumble flow achieved by endoscopic PIV measurement

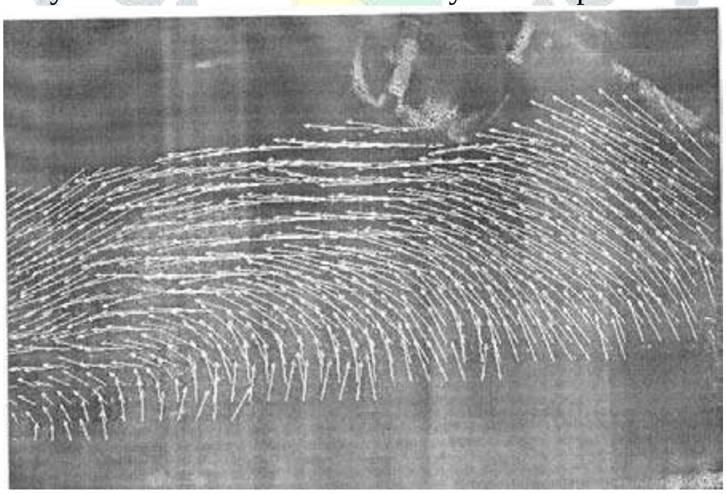

Figure 5. In-cylinder tumble flow achieved by standard PIV measurement

Laser Induced Fluorescence (LIF)

Laser induced fluorescence is spontaneous emission from atoms or molecules that have been excited by laser radiation. The basic process of LIF and an excitation spectra of NO are shown in the Figure 6 [8]

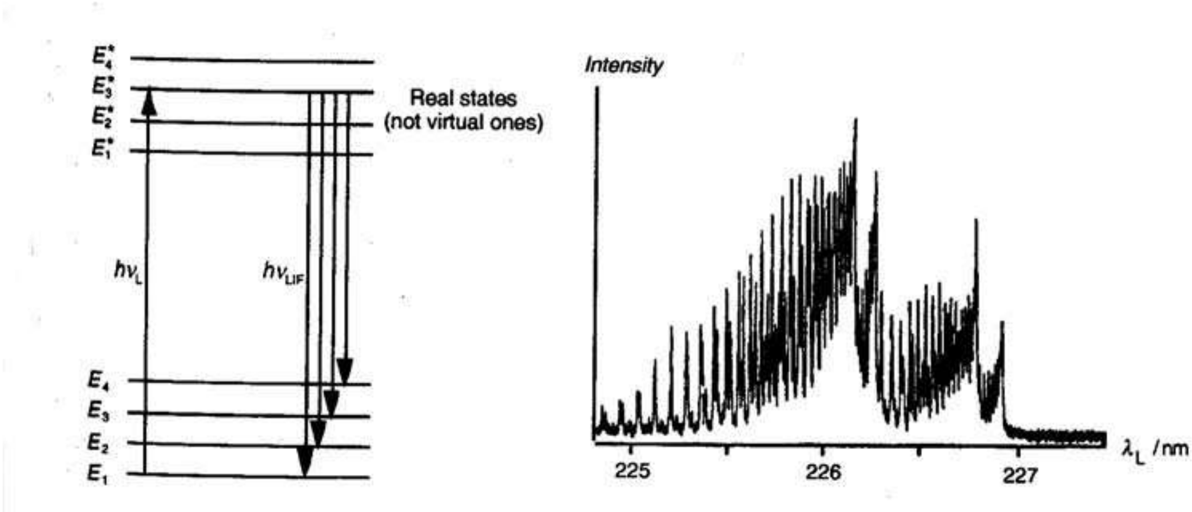

Figure 6. Basic process of laser induced fluorescence (LIF) and an excitation spectrum of NO

Since the transition takes place within the electronic levels in LIF, an energetic light source has to be used to induce fluorescence. The fluorescence produced can be measured by a photo diode detector. Advantages of LIF are the high sensitivity and selectivity, because fluorescence scattering cross section is typically a million times larger than the Rayleigh scattering cross section. Many intermediate species like H, O, N, C, OH, CH, CN, NH, HNO, SH can be measured using LIF though it is widely used for OH radical measurement. The intensity of the signal is dependant upon the density of the species being probed. Therefore with the correct calibration, and knowledge of the temperature, local composition, specific species densities can be obtained. If two different transitions are probed, ratio of the two intensities can be related to temperature via the Boltzman relationship. Temperature measurement using LIF have been carried out using NO or O2 as the thermometric species [9]. Figure 7 shows LIF measurement of profiles of temperature, OH and NO absolute particle concentration and CH relative concentration in a premixed laminar flat methane-air flame at p=40 mbar. Finally, velocity measurements have also been made using LIF utilizing the Doppler Effect [9]. LIF technique however has the limitations of a complex signal interpretation and detects fluorescent molecules only.

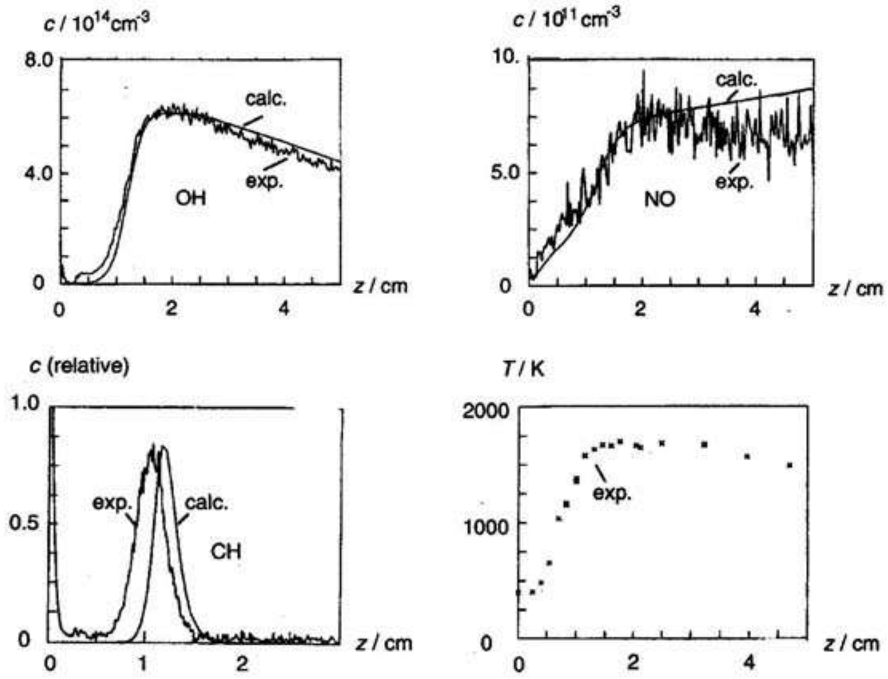

Figure 7. LIF measurement of profiles of temperature, OH and NO absolute particle concentration and CH relative concentration in a premixed laminar flat methane-air flame [8].

Chemiluminiscence

Chemiluminiscence is another simple and non intrusive optical technique to probe the hostile combustion environments. In principle it is the emission of electromagnetic radiation (UV, visible or near IR) by molecules or atoms resulting from a transition from an electronically excited state to a lower state in which the excited state is produced in a chemical reaction- mostly an oxidation reaction. Since the intensity of emission is proportional, in part, to the chemical production rate of the particular molecule, the chemiluminiscence intensity can be related to chemical reaction rate. For this reason chemiluminiscence has been used previously as a rough measure of reaction rate and heat release rate. Since these processes vary with the reaction path ways which is a function of equivalence ratios, chemiluminiscence can also be used to deduce the equivalence ratios. It has been shown that the ratios of chemiluminiscence from different molecules eg. OH*/CH* and C2*/OH* vary with equivalence ratio in simple flames. Intensity ratio of CH*/OH* was recently followed to measure equivalence ratio in high pressure lean burning combustors [10]. Moreover, OH* and CH* chemiluminiscence signals from these systems were used to detect the lean blow out limits [10]. Flame emission wavelengths for a few common combustion radicals and products are given in Table 1.

Species	Wavelength (nm)
CH	420-440
C_2	460-475,510-516
CN	359,389
H_2O	Broad band around 600
OH	308

Table 1. Flame emission wavelength for common combustion radicals and products.

It has been shown in a recent study on premixed LPG-air flame that ratios of intensities of radiations for various radicals in the visible region i.e. C2*/CH* and CH*/H2O* vary linearly with the equivalence ratio and hence can be used to estimate the local equivalence ratio. Variation of equivalence ratio with intensities obtained for different species ratio is shown Figure 8 [11].

High speed chemiluminiscence imaging (primarily from CH*) has been recently employed for measuring the laminar burning velocity of premixed hydrocarbon-air flame [12]. Time resolved measurement of flame radius and overall flame morphology could be studied by this technique. The technique is perceived as superior to schlieren techniques which only identify the location of maximum density gradient. Figure 9 shows the flame chemiluminiscence images for atmospheric propane-air flame at thermo-diffusively (a) stable (φ=1) an (b) marginally stable (φ=1.32) conditions.

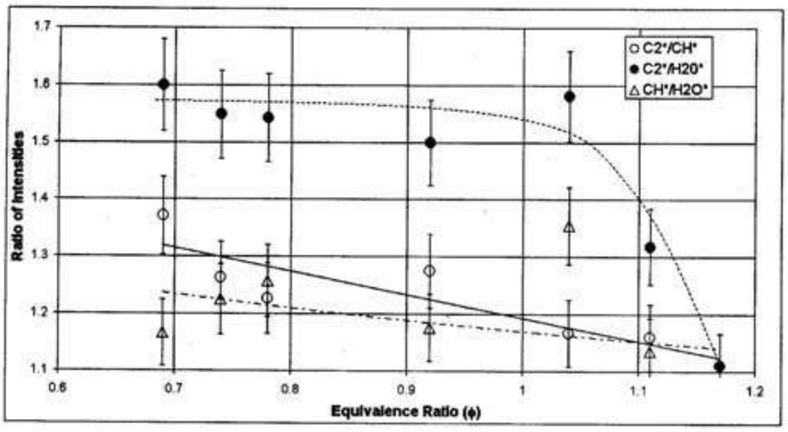

Figure 8. Dependence of ratio of radiation intensities on the equivalence ratio

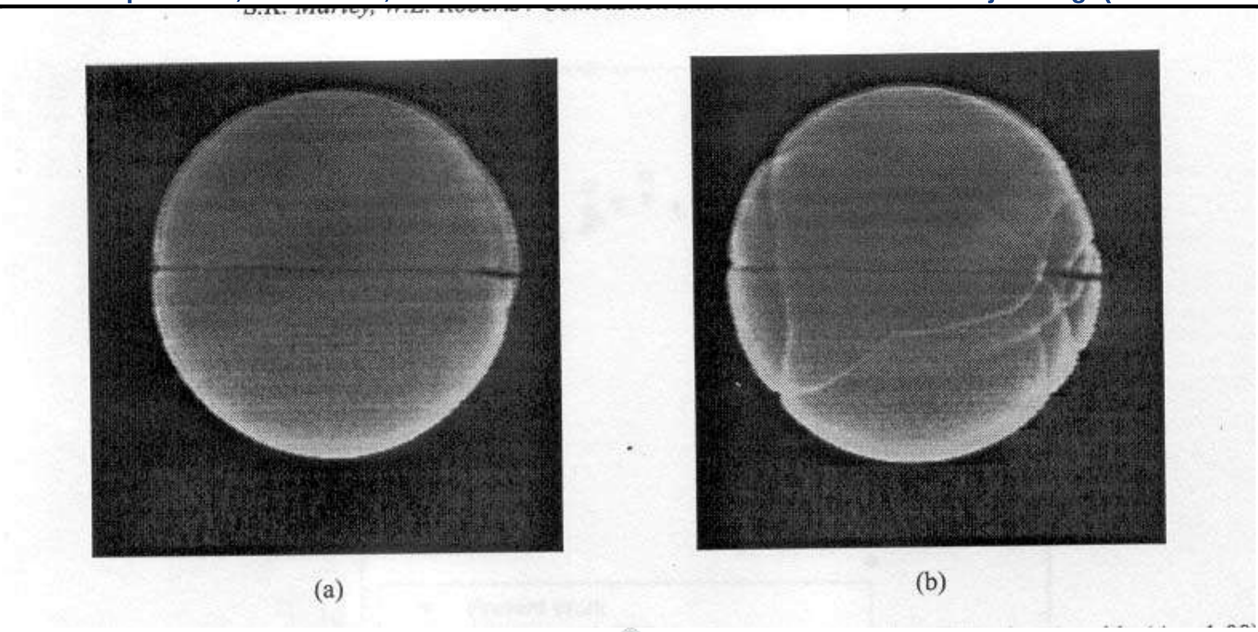

Figure 9. High speed flame chemiluminiscence images of propane-air flames at different equivalent ratios (a) φ=1 (b) φ=1.32

Conclusion

The article is meant to give a general overview of the recent advances in combustion diagnosis and is not exhaustive. There are several other techniques either new or adapted to combustion studies only recently, but are encountered less often in combustion literature. The diagnositics discussed in this article are evidently very sophisticated and therefore very expensive. Seldom do we come across any single research group having access to all these. Also the instrumentation system is becoming so complex that the combustion specialist often finds himself somewhat marginalized in his own laboratory. There is perhaps a need for a different kind of training to the prospective combustion scientist which includes electronic instrumentation, laser optics and signal processing as applicable to combustion studies.

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