

ADVANCED COMBUSTION DIAGNOSTICS



OPTICAL MEASUREMENT SYSTEMS DELIVERING RESULTS



Optical Systems Provide the Solution for Combustion Characterization



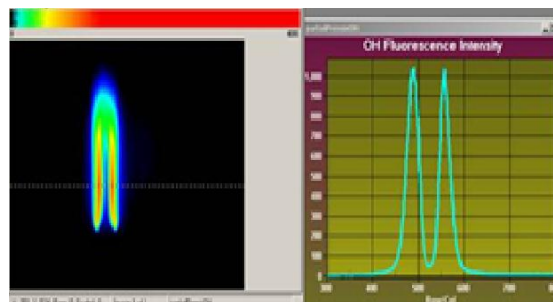
Optical systems are ideal for combustion diagnostics because the non-invasive nature of these systems allows measurements to be taken without inserting a probe into the measurement region. Further combustion environments, such as in diesel engines and commercial burners, can be hostile and restrictive; hence optical techniques provide the benefit of accessibility and safety along with accurate results.

TSI offers a number of optical systems especially suited to combustion diagnostics and characterization. They can be categorized as:

- Planar Laser Induced Fluorescent (PLIF) imaging system
- Laser Induced Incandescence (LII) system
- Laser induced Rayleigh Scattering (LRS) system
- Particle Image Velocity (PIV) system
- Phase Doppler Particle Analyzer (PDPA)

Each of the systems can be used to analyze different aspects of combustion and diffuse flames. The advantages of optical techniques are numerous:

- Non-intrusive
- Instantaneous
- Excellent spatial and temporal resolution
- Upgradeability from one optical system to expand capability by adding hardware
- Expandable from 1D to 2D or 3D; from single point to planar



Profile of OH in a diffused flame



PIV measurement
(U of California, Riverside, USA)



OH measurement
(IIT Kanpur, India)

Combustion and Flame Characterization

Various aspects of combustion and diffusive flames can be resolved. Some of the optical techniques are applicable to a number of measurements, essentially using a very similar hardware arrangement, but operated in different light scattering modes to achieve the desired results.

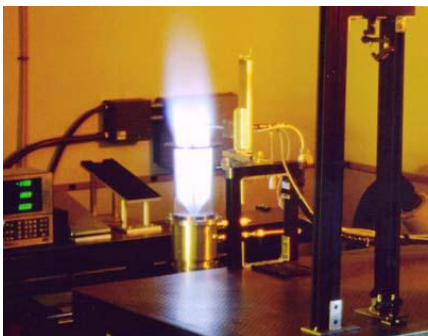
Measuring technique	Characteristics	Measurement Results
PLIF	Flame radicals in reaction zone	Species Concentration of OH and CH
PLIF	Flame pollutant analysis	Species concentration of NO, CO, and SO ₂
LII	Soot analysis in flame	Concentration profile of soot
LRS	Flame temperature	Profile of temperature
PIV	Flame velocity and mixing	Velocity field in flame
PDPA	Flame velocity and propagation	Velocity and size of particulates

PLIF-based systems are generally used to investigate the flame front (OH), the flame reaction zone (CH) and the quantity of pollutants (CO, NO, SO₂) generated from the combustion process. Soot formation is inherent in many flames and the LII technique provides details on the amount of soot generated to determine the burning efficiency. PIV systems are remarkable for 2D and 3D velocity measurements of flow fields in flames. PDPA systems are particularly useful in determining the velocity and size of particulates formed in combustion.

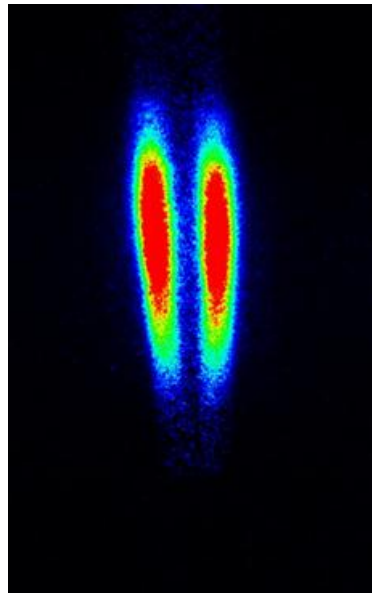
The resultant quantity of the measured component often requires calibration to be performed in order to relate the results to known physical quantities. Systems with the most flexibility provide in-situ calibration which is desirable because it allows the calibration to be more closely related to the actual operating environment.



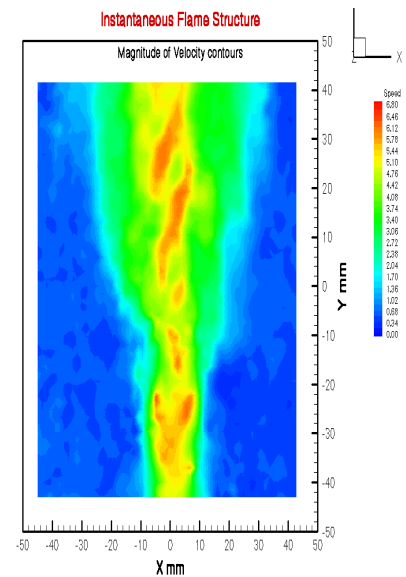
Flame diagnostics with PLIF
(ERC, Laguna Hills, CA, USA)



Single Can Combustor study
(ERC, Laguna Hills, CA, USA)



OH concentration profile (Harbin
Institute of Technology, China)

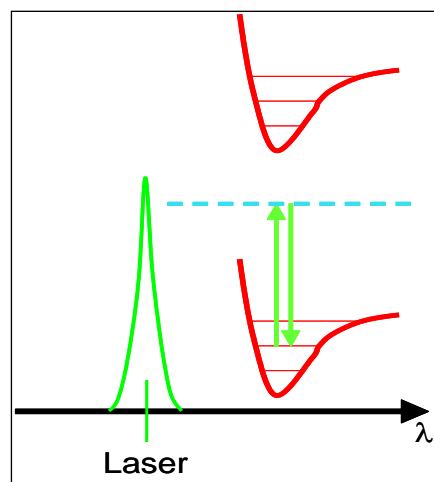


Flame velocity profile
(Stanford University, CA, USA)

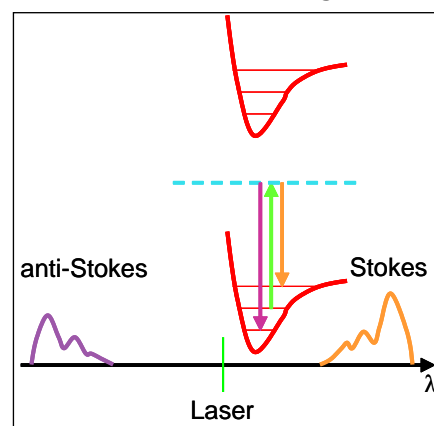
Light Scattering Processes

Knowledge of light scattering is important to the understanding of how the various optical techniques work for different measurements. There are two primary types of light scattering processes, elastic scattering and inelastic scattering. Elastic scattering involves no energy exchange between the incident photons of light and the scattering molecule or particle, and the scattered light is the same wavelength as the incident light, whereas during inelastic scattering there is an energy exchange (and the scattered light is generally at a different wavelength from that of the incident light). Elastic scattering processes include Mie scattering and Rayleigh scattering, while inelastic scattering processes include Raman scattering and Fluorescence.

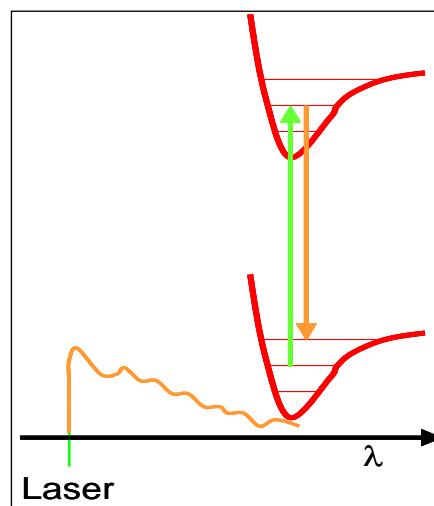
Elastic Scattering Processes	
Mie scattering	Mie scattering happens when the wavelength of light is much smaller than the size of the objects that scatters the light (particles). It is this process that is used to make PIV and PDPA measurements and the scattered light is the same wavelength as the incident light.
Rayleigh scattering	Rayleigh scattering occurs when the size of the scatters (molecules) is much smaller than the wavelength of light. The scattering efficiency scales as the fourth power of the frequency of light. The intensity of Rayleigh scattering can be used to measure density, pressure, or temperature under some circumstances.
Inelastic Scattering Processes	
Raman scattering	Raman scattering takes place, as depicted in figure on the right, when the energy associated with the incident photons excites the target molecules to a "virtual" energy level. These excited molecules very rapidly fall to lower energy states. Molecules that fall back to a state of lower energy than the initial state emit photons of shorter wavelength (blue shifted) than the incident light and it exhibits anti-Stokes Raman scattering (shown as the violet curve). Raman scattering is species dependent hence can be used to make concentration measurements, as well as temperature measurements.
Laser-induced fluorescence	Laser-induced fluorescence is a process during which incident photons are of the exact energy to excite the target molecules from a lower quantum energy state to a state of higher energy. Subsequently, the excited molecules spontaneously relax to a lower energy state and emit a photon whose energy equals to the energy difference between the two states. When the molecules relax to a lower energy state, they emit photons of a different wavelength than the incident light, which is referred to fluorescence (shown as the orange line in the figure to the right). The Laser induced fluorescence is ideal for the measurement of species due to the shifting of the wavelength by the species.



Rayleigh Scattering



Raman Scattering



Fluorescence

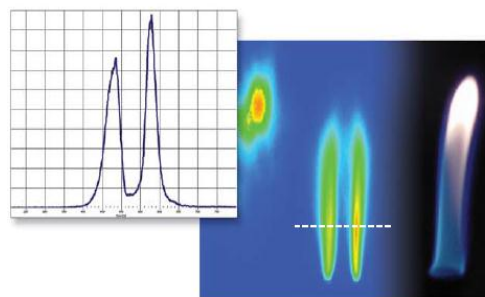
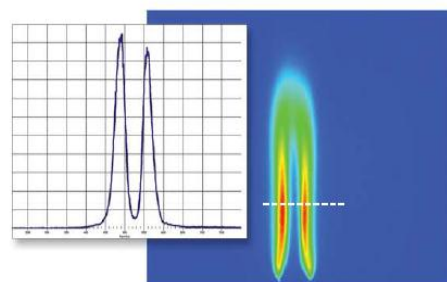
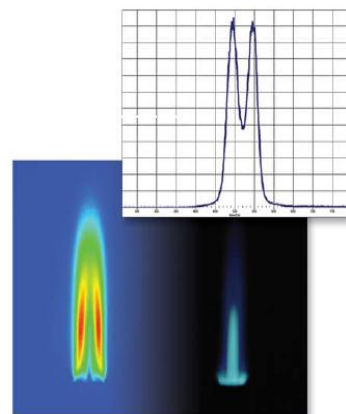
Measurements of Flame Radicals and Pollutants

The location and nature of the reaction zones are among the most fundamental aspects of combustion. Knowledge of these reaction zones is central to improving the understanding of combustion and the associated production of emissions. In addition, the information is useful for the development of predictive computer models and for guiding the design of future combustion burner with higher efficiencies and lower emissions.

PLIF imaging of the combustion radicals provides a means of studying the combustion reaction zones. Both the CH and OH radicals have been used in burner experiments to visualize the reaction zones on hydrocarbon flames. CH is difficult to measure (high-cost, low signal) while OH has a much stronger signal; hence, OH measurement is typically performed to show the reaction zone of the flame.

Emission control of pollutants from combustion is of great interest. The understanding of the pollutant emission and its chemistry helps for better design of the burner. The PLIF technique again is a good method to measure some of the common pollutants, NO, CO, SO₂, generated from the combustion process.

Imaging systems for PLIF measurements may vary depending upon the species (radicals or pollutants) to be measured. A typical system consists of a Tunable Dye laser, Intensified CCD (ICCD) camera, laser light sheet generator, synchronization unit, control software and filters. The Tunable Dye laser is preferred because the desired wavelength can be obtained to excite the species of interest. The fluorescent signal is then collected by the ICCD camera with the appropriate filter. Analysis performed by the software gives the results of the concentration of the species.



OH fluorescence for different type of flame configurations



PLIF system for OH measurement
(IIT Kanpur, India)

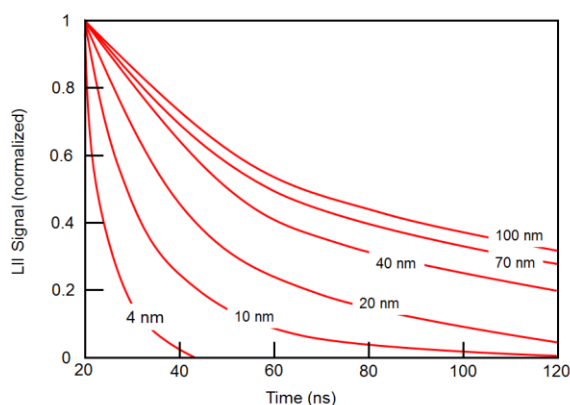


Multistage Combustor Test stand
(ERC, Laguna Hills, CA, USA)

Analysis of Soot Formation

Soot is related to incomplete combustion which is an indication of inefficient combustor performance. Laser-Induced Incandescence (LII) is useful for soot measurement because it combines the benefit of elastic scattering and line-of-sight extinction and gives excellent spatial resolution. Soot particles are comprised of branchy aggregates of nominally spherical particles of graphitic carbon on the order of a few tens of nanometers. LII of soot occurs when soot particles absorb laser illumination. When the laser energy is high, the particle temperature will rise to a level where the soot particle will glow or incandesce. The incandescence is a broadband emission, essentially blackbody emission modified by the spectral emissivity of the material. The emission signal primarily corresponds to the amount of laser energy absorbed and is most sensitive to the concentration or volume fraction of soot. As a result, the concentration or volume information can be detected.

A typical system for soot measurement using LII is made up of a pulse laser operated at 532 nm with high energy output (300 mJ per pulse or higher), light sheet optics, a gateable ICCD camera, synchronization unit, broadband filter and the control software. The broadband filter (450 ± 25 nm) is placed in front of the camera to minimize the interference from scattered light. Further reduction of the scatter light can also be achieved by gating the camera to a few tens of nanoseconds. The decay of the LII signal is a function of the particle size as indicated in the graph below (red line with the corresponding particle size). The adjustment of the gate time in the camera can be optimized to give strongest signal.



Decay of LII Signal with Time for various Particle Sizes

Laser-induced Rayleigh Scattering for Temperature

Laser-induced Rayleigh scattering (LRS) is an important diagnostic tool for the measurement of flame structure as well as density and mixture fraction. If the pressure is known on the flame, the density measurement can be converted to temperature. The technique provides the global image of the temperature distribution across the flame illuminated by the laser light.

The LRS signal is linearly dependent on the gas number density and excitation laser power. It is also unaffected by quenching and saturation. However the elastic nature or Rayleigh scattering is difficult to be decoupled from the spurious elastic background like Mie scattering from particles and multi-scattering from optical windows. Hence an atomic or molecular filter, made of an optical cell filled with atomic or molecular gas, is generally required to provide the narrow absorption line to be detected.

The typical configuration of system for LRS is made up of an injection seeded single mode Nd:YAG laser, ICCD camera, light sheet optics, synchronization unit, atomic or molecular filter, and control software. Proper interpretation of the intensity is critical in achieving the accurate quantitative results of temperature.

PIV and PDPA for Flame Velocity and Sizing of Particulates

PIV is an imaging technique to obtain flow field information in a plane. Typically solid seed particles are needed to be injected to the flame to provide the signal for velocity. The PIV technique is very robust and provides excellent flow field information of the flame, mixing and flame front characteristics. In order to collect the signal efficiently, a band pass filter is normally used to allow the camera to detect only the scattered laser light from the seed particles, not the intensity of the flame. 3D velocity information can be obtained when two cameras are used in a stereo PIV configuration. Further time-resolved measurements can be taken when a high speed camera and laser are employed.

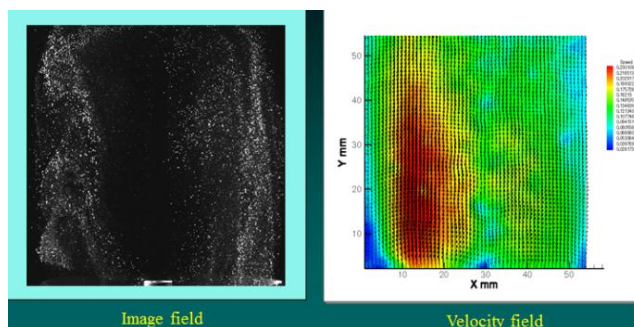
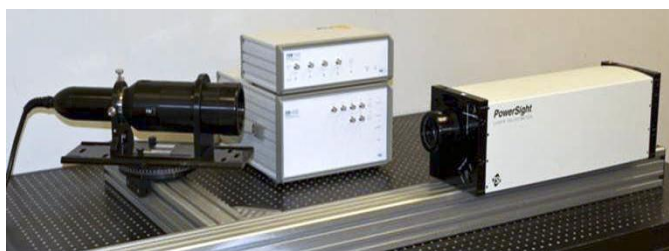
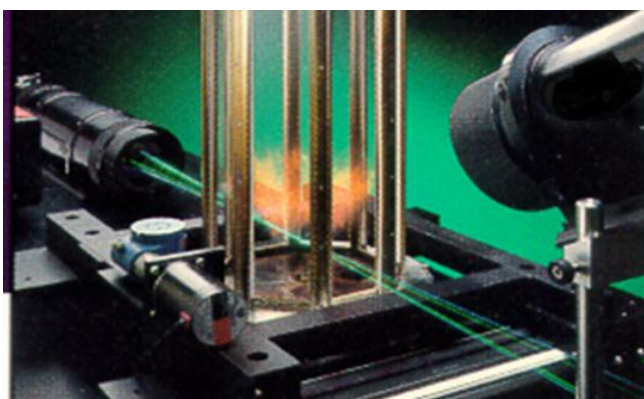


Image and velocity field of Combustion measurement in Microgravity using PIV (CNRS Orleans, France)

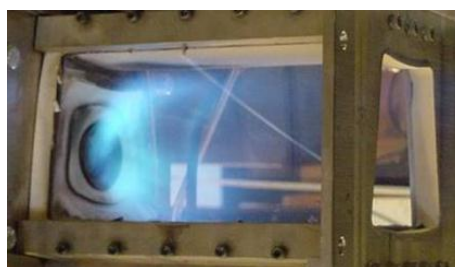
PDPA is a technique based on the Doppler shift of the scattered light signal from the particulate, and it provides simultaneous velocity and size information. The technique is a single point measurement with extremely high spatial resolution of less than 100 microns. It also provides very high temporal resolution to track



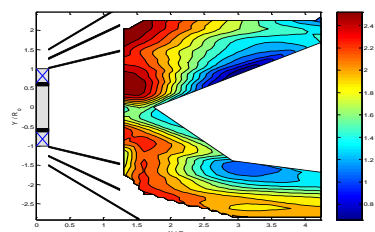
the concentration of particulates going through the measuring volume. The PowerSight PDPA system shown in the picture above can be expanded from 1D to 2D or 3D to allow all velocity components of the particulate in the flame to be measured. To obtain good signal, a band pass filter is used in the Receiver to allow only the scattered light from the particulates to be measured. The system can also be traversed enabling mapping of the particulate distribution.



PDPA arrangement for flame velocity



Lean Low NOx Combustor (Georgia Institute of Technology, GA, USA)



SMD for the NOx combustor (Georgia Institute of Technology, GA, USA)

The TSI Approach to Combustion Diagnostics

Integrated System Approach

TSI offers fully integrated optical systems that operate from a single, easy-to-use and seamless platform. For imaging based systems, such as PLIF and PIV, the Insight 4G software package is the key component which can be shared across different applications. Insight 4G possesses numerous features that facilitate PLIF measurements. One of the most important aspects of an integrated system is the timing control of all of the interacting components, which include the Tunable Dye laser, the ICCD camera, and the flow system being observed. A unique graphical approach has been implemented into Insight 4G that allows the user to validate and adjust the timings of individual components using an intuitive visual timing diagram, which depicts all events and their duration. PLIF images can be either single shot images or can be CCD-integrated over numerous laser pulses. The timing diagram approach allows one to easily set and verify the PLIF image capture with respect to the laser sequence and the PLIF capture process.

Calibration hardware and Image Processing features

There are many unique capabilities in PLIF calibration and processing that are provided by the integrated system. Some of the unique features with regards to the calibration and image processing are as follows:

- Dynamic laser energy measurement
- In-situ calibration capabilities
- Interpolation calibration capabilities
- Automatic background correction
- Automatic correction for variations in laser sheet intensity
- Automatic dark noise correction
- Automatic correction for variations in laser pulse energy
- Automatic correction for variations in individual pixel response
- Single-shot capture or multiple-shot integration on the CCD
- Flat Flame burner to be supplied as calibration hardware

System Expansion for Other Applications

The components employed in the PLIF system can be easily expanded for the LII and laser-induced Rayleigh scattering for soot concentration and temperature measurements respectively. Many of the hardware components remain the same and serve as the basic platform. The intent is to allow you to configure the system to meet your specific applications while providing the options to expand for other future research activities.



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