Non-invasive combustion diagnostics

PLIF, PIV and next generation imaging detectors

Combustion processes, if uncontrolled, are inherently inefficient and increasing the efficiency of combustion in engines, gas burners and furnaces is a significant challenge for the future due to limited fossil fuel resources and their effects on the environment.

To examine the structure and composition of flames requires cutting edge laser imaging techniques such as Laser Induced Fluorescence (LIF), Particle Image Velocimetry (PIV), scattering experiments (Raman-, Rayleigh- and Mie-) and Spectroscopy (Emission and Absorption) [1][2][3]. These techniques are favored and commonly used as they allow non-invasive multi-parameter measurements with high resolution. Some of the most commonly used laser diagnostics techniques to examine complex combustion processes are Particle Image Velocimetry and Planar Laser-Induced Fluorescence (PLIF) and to a lesser extent chemiluminescence. These form the backbone of the science of combustion imaging and diagnostics and are ideal for in-situ real-time recording of the complex dynamic gas and fuel processes occurring in a flame.

Planar Laser-Induced Fluorescence (PLIF)

In PLIF, a pulsed wavelength tuneable laser source forms a thin sheet of light [3], which criss-crosses the flow field (flame area) under study. When the laser wavelength is resonant with an optical transition of a species (chemical ion or molecule) in the flow, a fraction of the incident light will be absorbed at points within the illumination plane. Some of the absorbed photons are subsequently re-emitted with a new spectral distribution, which is different for each molecule/species and also varies with the local flow field conditions in the flame.

Fluorescence is produced by the excitation of species such as OH in the flame by a Nd:YAG pumped dye laser. The emitted fluorescence is collected and imaged onto a solid-state array camera, which is typically coupled to a ‘gated’ image-intensifier to provide snapshots of the fast flows with improved sensitivity, as the intensity of species of interest emitted fluorescence can be extremely low.

The amount of light (fluorescence) detected by pixels in the camera depends on the concentration of the species being studied within the measurement zone of the flame and the local flow field conditions, i.e., temperature, pressure and mixture composition. PLIF is a useful technique for flame front studies in reacting flows. The application areas vary from laboratory burners to commercial internal combustion engines and gas turbine burners. PLIF is ideally used for the measurement of concentration/mole fraction of species such as Na, OH, NO, O₂, CH, CO or acetone, localised temperature, velocity, and pressure. Applications include:

- Discriminating OH and CO imaging for flames and combustors
- NO imaging for NOx production in gas jets
- Acetone imaging for fuel and air mixtures
- Temperature imaging in flames and supersonic/hypersonic flows
- Velocity imaging for supersonic jets

Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a laser-based optical technique for the characterization of flow and turbulence dynamics in combustion processes. Typical PIV measurements use dual laser pulses to probe the flow field and determine the two velocity components of features of interest in a single plane simultaneously [3a]. A truly useful technique for examining flow processes in a wide range of situations, PIV has now reached its zenith with the availability of high speed camera and data processing systems. The high speed and fast shutter rate of modern cameras using CMOS or interline technology, which typically run at 10’s of frames per second, means that PIV can provide first-rate images. However, in some instances where supersonic flows are being examined, even enhanced frame rates may not be sufficient to obtain a non-blurred image, and in these cases an image intensifier with 10’s or 100’s of nanosecond shuttering capabilities is used to provide extremely sharp images. This kind of camera/detector set up is also useful when a strong unwanted optical background could interfere in the same optical path as the required experimental signal. In these cases the fast gated detector allows the exposure of the sensor only during the period when the signal (scattering or fluorescence) being studied is emitted, hence minimizing the amount of unwanted background accumulation between laser pulses.

Chemiluminescence Imaging (CI)

CI is a simpler technique also used for flame studies, which instead of laser light uses chemical excitation of the species under study. The camera records the light emitted from chemically excited species such as OH, which are then denoted OH* because they are in an excited state prior to emission of a photon as they return to the ground state. CI is useful in situations where it is technically difficult or too costly to apply PLIF such as optical engine diagnostics, where to follow single-cycle events it is preferred to acquire image data with high repetition rates.

Applications

A ground breaking 2015 study [4] of the combustion of coal particles used high-speed planar laser-induced fluorescence measurements of the hydroxyl radical in the boundary layer. Using a laminar flow reactor to provide an oxygen-enriched exhaust gas environment time-resolved imaging of the OH distribution at 10 kHz allowed identifying reaction and post-flame zones and gave access to the temporal evolution of burning coal particles. This experiment was able to show, for the first time, the distribution of OH in the flame boundary areas. In 2012 an optical study [5] of hydrogen combustion in a novel spark-ignition research engine used both PLIF and CI to characterise the combustion processes. Crank-angle resolved flame CI images were acquired and post-processed for a series of consecutive cycles to calculate in-cylinder rates of flame growth.

While OH-PLIF was also applied to an in-cylinder plane below the spark plug to record detailed features of the flame front for a series of engine cycles. The combination of these two methods was able to compare gasoline burning to hydrogen burning and to provide new data about the underlying flame mechanisms, which will aid the development of hydrogen powered engines. Other more complex CI and PLIF imaging applications are now using DFCD-based (Digital Flame Colour Discrimination) processing methodology [6] and multiple camera (in this case 12 cameras) Flame chemiluminescence tomography (FCT) [7] to provide 3D measurements of flame
geometry and convey the multi-dimensional aspect of combustion. These experiments demonstrate that a combination of PLIF and chemiluminescence techniques is ideal for detailed flame studies e.g., local flame extinction events, although PLIF can usually provide more detailed information due to higher spatial and temporal resolution.

**Andor detection solutions for non-invasive, laser-based combustion diagnostics**

The Andor iStar sCMOS intensified camera is ideally suited for PLIF / Chemiluminescence and time-resolved PIV. It offers a sensor with a high resolution 5 megapixel matrix for some of the highest resolution and sharpest images possible. With high speed accurate gating of <2ns, the ability to record 4,000 fps and its ease of use and integration with high speed computing/data systems the iStar sCMOS provides state-of-the-art imaging technology for laser-based, time-resolved combustion diagnostics. The iStar sCMOS sensor architecture and highly accurate gating capabilities also allow acquisition of consecutive PIV images with an optical interframe down to 300 ns.

**References:**


