

Chapter 2

Non-interfering Diagnostics for the Study of Thermo-Fluid Dynamic Processes

The conversion of chemical energy into mechanical power, operated by internal combustion engines, involves a great number of complex phenomena that often occur in transient thermo-fluid dynamic conditions. The majority of these phenomena are affected by nonlinear dynamics, thus requiring appropriate compensation techniques.

The analysis and comprehension of these nonlinear processes is a basic requirement for the design of effective control solutions, able to optimize the combustion processes in terms of engine power, efficiency, and emissions.

In this chapter, we present some advanced non-interfering optical diagnostics that allow to study in detail the reasons and the effects of the nonlinear behavior of many processes occurring in internal combustion engines.

The internal combustion (IC) engine is designed to provide power from the energy that fuel contains. More specifically, the chemical energy of fuel and air creates a mixture that burns to produce mechanical power. There are various types of fuels that can be used in IC engines, which include liquid (gasoline, Diesel fuel, biofuels) and gaseous (methane, propane, hydrogen) substances. The output power produced by an IC engine results from the fuel that it uses and its mechanical parts. In an internal combustion engine, a piston moves up and down in a cylinder, and the power produced is transferred through a connecting rod to a crankshaft. Most engines operate on what is known as four-stroke cycle. Each piston completes four separate strokes while turning a crankshaft. A stroke refers to the full travel of the piston along the cylinder, in either direction [1]. Both spark ignition (SI) and compression ignition (CI) engines use this cycle, which comprises:

- Intake stroke, in which fresh air enters and the fuel can start to spray;
- Compression stroke, in which the fluid and fuel are compressed and, at end, the combustion can occur;
- Expansion stroke or power stroke, when the combustion evolves and exhaust gases, including pollutants, are produced;
- Exhaust stroke, when the exhaust gases are emitted.

The processes occurring during these cycles consist of a complex interaction of homogenous and heterogeneous chemistry and transport processes. The processes involved in internal combustion engines (ICE) are two-phase, turbulent mixing-controlled, and they include short timescale phenomena such as turbulence production and dissipation, spray breakup and evaporation, and pollutants formation.

As consequence, in order to carry out appropriate investigations, non-intrusive diagnostic techniques with high temporal and spatial resolution must be considered. In these years, the science of optics has played an important role in the measurement and understanding of combustion phenomena, including not only laboratory flames but also practical devices such as the internal combustion engines. Optical diagnostics allows to obtain pertinent knowledge in complex systems where non-linear and very fast phenomena occur. In particular, the use of optical engines with wide accessibility, improved detectors, and ultra-fast light sources tools is considered of great interest, as it allows real-time and high spatial resolution characterization of the phenomena without any modification of the different phases occurring.

There are numerous methods applied in optical engines, and just a few of them have the potential of being applied in practical engines. Optical diagnostics operate in a broad spectral range, from ultraviolet (200 nm) to infrared (10,000 nm). In each spectral domain, it can apply diagnostics based on emission, absorption, and scattering fluorescence measurements. The decision for application of a specific optical technique is always based on the requested information other than the efforts and chances to gain the required results with a given method.

The present chapter provides an overview of optical methods and their application to the study of the complex phenomena occurring in internal combustion engines.

2.1 Air Motion

The study of fluid mechanics in the cylinder in terms of mean motion and turbulence characteristics can be made by means of Laser Doppler Anemometry (LDA), also known as Laser Doppler Velocimetry (LDV), Particle Image Velocimetry (PIV), and Phase Doppler Anemometry (PDA). By these techniques, it is possible to analyze the air motion, which contributes both to the air/fuel mixing and to the flame propagation process during combustion. The LDA is a technique that uses the Doppler shift in a laser beam to measure the velocity [2]. It is an optical method, tightly related to both the physical and geometrical optics, and it is a widely accepted tool for investigating fluid dynamics with gases and liquids. As the fluid moves through the probe volume with small seeding particles, the information of the flow velocity is generated. In particular, when a particle passes through the intersection volume (measurement volume) formed by the two coherent laser beams, the scattered light, received by a detector, has components from both beams.

The intensity of the scattered light has a fundamental frequency that is connected to the particle velocity.

LDA usually provides single-point velocity statistics, typically in two directions, while PIV provides instantaneous velocity images. LDA can be arranged to measure local flow velocity, even the smallest length scales of the flow (the Kolmogorov scale), and it provides single-point statistics, which are well matched to time-averaged modeling approaches (e.g., RANS models). While it is usually quite difficult to acquire PIV data down to the Kolmogorov scale, PIV provides additional insight by allowing researchers to visualize an entire field and thus to visualize phenomena like spatial correlations that are well matched to LES models. For reasonably laminar or transitional flows, PIV is often used by itself. For turbulent flows as air motion in the ICE, the problem becomes much more challenging. LDA and PIV are often used in complementary ways for such flows. Both LDA and PIV require that the flow be seeded with particles, and this seeding process is usually different from one flow to the next. To apply PIV to new environments usually requires the researcher to evaluate the needed seed density for good spatial resolution. During the combustion, this technique lacks in sensibility: very high seed density can affect flame temperature by enhancing radiation heat transfer from the flame. One must also be careful to consider factors like inter-pulse spacing to produce best quality correlation of the two PIV images. In addition, three-dimensional flows require one to consider out-of-plane motion and its effect on accuracy. To apply PIV to challenging environments can require special arrangements, such as a fast shutter to avoid high background levels caused by flame radiation.

2.2 Mixture Preparation

Mixture preparation is of major importance when designing next generation internal combustion engines. To minimize engine out emissions, such as CO_2 , CO , NO_x , and particulate matter, while enhancing performance and fuel economy, it is crucial to have control over this parameter. The investigation of the fuel and air mix within the cylinder can be carried out by several techniques that have been widely used in the past and now greatly improved by new intensified charge-coupled device (ICCD) cameras, complementary metal-oxide semiconductor (CMOS) cameras, and less expensive laser sources.

During the last decade, various laser techniques have clearly shown their effectiveness in measurement and diagnostics of various combustion phenomena. These techniques have the great benefit of being able to make non-intrusive measurements (no physical probe introduced in the combustion zone), to have high spatial ($<0.001 \text{ mm}^3$) and temporal resolution ($<10 \text{ ns}$), and they can measure several points/species in one laser pulse. In addition, many techniques can provide two- or even three-dimensional information.

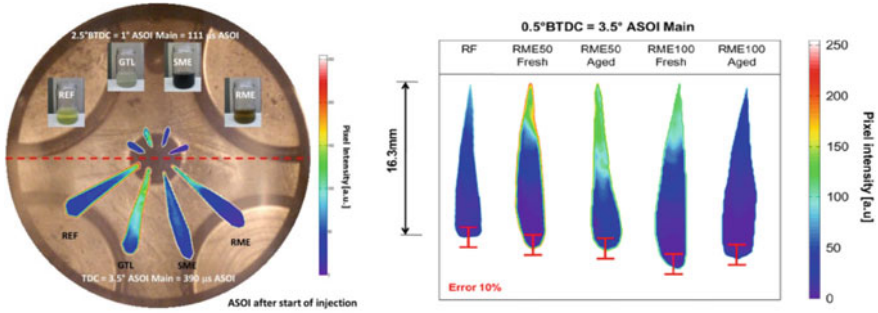


Fig. 2.1 Characteristics of different fuels [commercial Diesel (REF), GTL and several biofuels (SME, RME blends and RME aged)] obtained by luminous intensity distributions in the jet

They are based on the high-speed direct, backlight, and Schlieren imaging [3] and can be applied to study spray atomization, the fuel penetration and dispersion, as well as the evaporation phenomena. Although cycle resolved, these techniques cannot provide spatial quantitative information on the air–fuel mixing in the combustion chamber, but only statistical data can be obtained, owing to the instability and highly turbulent nature of Diesel sprays and of high injection pressure of new gasoline direct injection spray. Nevertheless, the liquid tip penetration and cone angle can be obtained with good accuracy for the main injection, meanwhile less information can be obtained for short pre- and pilot injections. Recently, interesting results about the pre- or pilot injection were obtained with use of infrared diagnostics. In [4], the visualization of the pilot injection process was obtained by means of an optical access in the piston head and by the presence of an inclined mirror for the collection of the images. The pilot injection was characterized by fast IR imaging. This innovative and non-conventional optical technique in the infrared was applied for the visualization of the liquid and vapor fuel. Other authors [5] performed in the infrared (IR) region of the spectrum black-body emission an imaging of the temperature reduction caused by the impingement of the spray on an electrically heated wall. However, the metallic (or fused silica) surfaces in the cylinder cannot be treated as a black body. Hydrocarbon fuels absorb IR light over broad wavelength regions. By measuring the attenuation of transmitted IR light, it would be possible to detect even thin wall films. A disadvantage is that optical access to the combustion chamber from two opposing sides is needed for a transmission measurement.

Developments in laser source and detection systems allowed to set new 2-D laser imaging diagnostics to obtain the spatial distribution of liquid and vapor of fuel inside optically accessible engines by simultaneous use of laser-induced Rayleigh and Mie scattering imaging, and EXCIPLEX technique, based on a fluorescence system. This latter technique, even if it can distinguish simultaneously between the spray liquid and vapor phases, needs of a fluorescence

dopant, and therefore, it is limited to oxygen-free atmosphere because the doping molecule is severely quenched by the oxygen and a surrogate fuel must be used [2].

A different technique, based on the principle of absorption of ultraviolet laser light by vapor fuel and the scattering of visible laser light by liquid fuel, seemed to give good results because it measures simultaneously the concentrations of vapor and liquid in an evaporating Diesel spray. Being an absorption technique, its drawback is the integration across the entire width of spray. The technique can be used in optical engines using a polychromatic light beam, and it is based on Lambert–Beer’s law. Considering that a light beam of an intensity I_0 is attenuated when it passes through a multi-phase spray, the transmitted light intensity I_t can be written as follows:

$$\frac{I_t}{I_0} = \exp(-K_{\text{ext}} \cdot L) \quad (2.1)$$

where L is the optical path length and K_{ext} the extinction coefficient that is equal to:

$$K_{\text{ext}} = -\frac{\pi}{4} C_n \int Q_{\text{ext}} N(D) D^2 dD \quad (2.2)$$

where C_n is the number density of droplets, Q_{ext} is the extinction efficiency, D is the droplet diameter, and $N(D)$ is the droplet size distribution function [2]. In the UV and visible range, the spectral extinction is due to different phenomena which can be separately analyzed [6]. Using the principle of absorption of ultraviolet light by fuel vapor and the scattering of light in the visible range by liquid fuel droplets, the concentration of both phases can be obtained. The visible light, which is not absorbed by both liquid and vapor phases, is attenuated only by the scattering caused by droplets. Therefore, the transmissivity of visible light by the fuel spray is equal to the transmissivity due only to the scattering caused by liquid droplets, as shown by the following equation:

$$\text{Visible : } \log\left(\frac{I_0}{I_t}\right)_{\text{Vis}} = \log\left(\frac{I_0}{I_t}\right)_{L,\text{sca}} \quad (2.3)$$

The ultraviolet light, which is absorbed by both liquid and vapor phases, is attenuated due to the absorption caused by vapor, to the scattering caused by liquid droplets, and to the absorption of liquid droplets according to the equation:

$$\text{UV : } \log\left(\frac{I_0}{I_t}\right)_{\text{UV}} = \log\left(\frac{I_0}{I_t}\right)_{V,\text{abs}} + \log\left(\frac{I_0}{I_t}\right)_{L,\text{sca}} + \log\left(\frac{I_0}{I_t}\right)_{L,\text{abs}} \quad (2.4)$$

The last two terms are much lower than the first one, so the UV transmissivity depends mainly on the absorption by fuel vapor [6].

Considering Eqs. (2.1) and (2.2) and experimental extinction data in the visible reported in the hypothesis of Eq. (2.3), it can be obtained:

$$\log\left(\frac{I_0}{I_t}\right)_{\text{vis}} = \left(-\frac{\pi}{4}C_n \int Q_{\text{ext}}N(D)D^2dD\right)L \quad (2.5)$$

From this equation, the mass concentration of fuel droplets per unit volume, C_d , considering the results of [6], can be expressed as:

$$C_d = \frac{2}{3L}\rho_f \frac{D_{32}}{Q_m} \log\left(\frac{I_0}{I_t}\right)_{\text{vis}} \quad (2.6)$$

where ρ_f is the liquid fuel density, Q_m is the mean extinction efficiency for the poly-dispersed particle cloud, and D_{32} is known as the volume/surface mean diameter (Sauter diameter), which can be obtained by Phase Doppler Particle Analyzer (PDPA) measurements or by the correlation of Hiroyasu [7]. Analogous expression can be obtained for the vapor concentration, C_v , considering Eqs. (2.1) and (2.4), as reported in [6]:

$$C_v = \frac{1}{kL} \log\left(\frac{I_0}{I_t}\right)_{V,\text{abs}} \quad (2.7)$$

where k is the molar absorptivity of the vapor fuel.

A comparison between liquid and vapor distribution for *n*-heptane and Diesel fuel, obtained from extinction measurements at different times, after Start of Injection, can be found in [8], where the measurements are carried out in an optical Diesel engine using a commercial Diesel fuel and *n*-heptane.

In order to better understand the liquid distribution of the different fuels, the injection images detected in the combustion chamber can be processed and converted on 8-bit scale. A scale of 256 colors is used to represent the several luminous levels into the jet (Fig. 2.1). The RME fuels show a denser liquid core with respect to the reference and a higher penetration because of the high density/viscosity.

2.3 Combustion

In the past, optical analysis of the intermediate steps from ignition to soot formation was generally restricted to the measurements of ignition delay, and the high-speed imaging was performed doping the fuel with copper to create a more luminous emission before the formation of soot. The lack of spatial and time resolution typical of these techniques has been partially overcome with the natural chemiluminescence imaging by using ICCD and CMOS cameras.

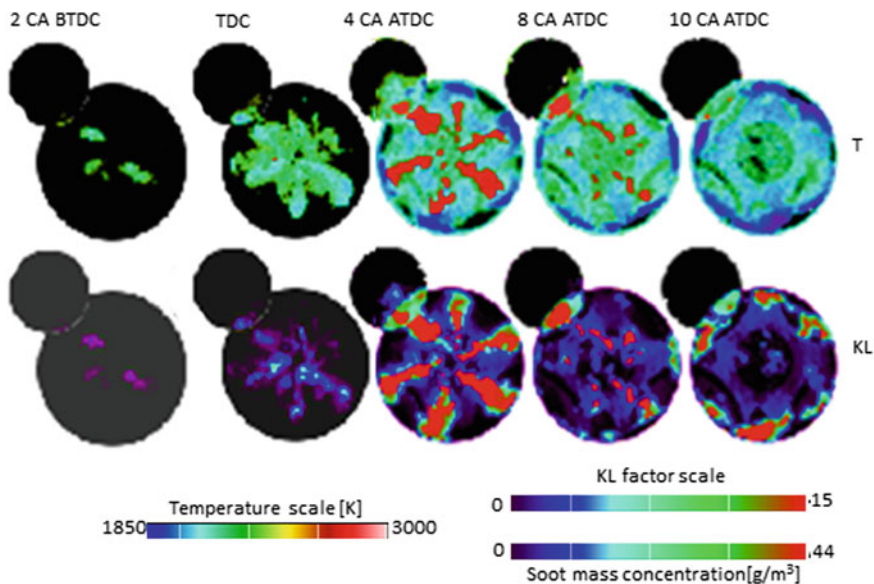


Fig. 2.2 Temperature and soot evolution in a Diesel engine

In [9], the combustion evolution in an optical common rail Diesel engine detected by chemiluminescence measurements using a visible narrow filter on a CCD camera is reported. By this diagnostics, useful information on turbulent evolution of flame in the combustion chamber and on the species involved in this spectral range can be obtained. Radiation of a Diesel flame is essentially due to thermal radiation of the soot particles formed under heterogeneous diffusion combustion of the fuel sprays. Its visible intensity is used to evaluate temperature and soot concentration comparing it with Planck's radiation formula. This "two color" method was applied to obtain the results presented in Fig. 2.2 for the same conditions reported in [9]. It is based on the use of two selected wavelengths (colors) in the spectrum, which are used to obtain, with an iterative procedure, the absolute temperature by Planck's formula.

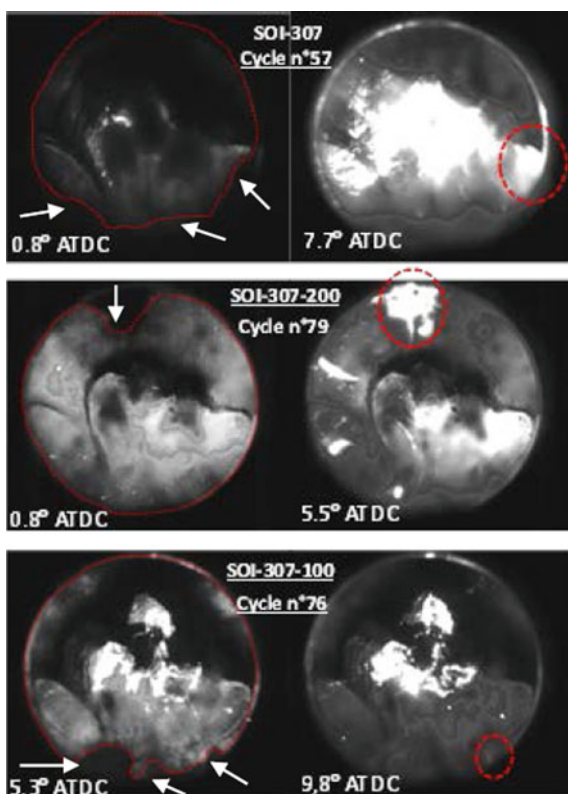
Analogous results can be obtained for SI engines, even if the soot produced is very low. In order to overcome this limitation and to consider the effect of cycle-to-cycle variation typical of SI engine, a CMOS camera is used in [10]. In this work, a selection of images detected during the combustion phase of ethanol and gasoline for injection pressures of 30 and 120 bar is shown. The images were obtained through an optical window on a piston of an optical accessible spark ignition (SI) engine. For both fuels, a luminous arc represents the evidence of spark ignition. It occurs at around 24° CA BTDC and persists until 15° CA BTDC, when the flame kernel is well observable, even if its luminosity is much lower than the spark. Then, the flame kernel moves from the spark plug in the combustion chamber, and it is the highest for the gasoline injected at 30 bar, whereas it

decreases when the injection pressure increases, due to a better fuel–air interaction. About ethanol, the soot amount production increases at the rise of injection pressure due to the amount of fuel impinged on the piston. In this case, it is important to note that at the opening of exhaust valves, the differences of soot amount in the combustion chamber decrease. Moreover, the development of the combustion process can be analyzed by means of a post-processing of the optical data. In particular, the flame front speed and radius, which are key parameters in the study of combustion process in spark ignition engines, can be evaluated.

These techniques also allow the detection of anomalous combustion occurring in SI engine known as knock. Knock is a consequence of a spontaneous ignition of a portion of the fresh mixture ahead the propagating flame. It gives the name to the noise transmitted through the engine structure. The noise, which sounds like a metallic ringing, different from the muted sound of normal combustion, is a consequence of the pressure waves generated by the abnormal combustion. The abnormal combustion suddenly releases a chemical energy that excites within the cylinder volume a local increase of pressure followed by oscillations. It is also generally accepted that spontaneous ignition begins at one or more exothermic centers in the end-gas region, as confirmed by optical probe measurements [11, 12]. Optical measurement methods are fulfilled requirements because the spontaneous nature of a self-ignition event and the high propagation velocity must be accounted for with adequate signal recording techniques, which detect in-cylinder gas signals and provide location of the knock signal origin [13–15].

Figure 2.3 shows typical knock conditions obtained in SI. The flame front profile has a concavity with a radius of curvature located in the opposite direction of the main propagation. In particular, SOI-307 (cycle n°57) flame outline presents more than one concavity, with a center of curvature at the bottom left or right of the chamber (intake valves). Instead, early split injection case (SOI-307-200) shows one wider concavity clearly visible in the exhaust valves, i.e., in the upper part of the frame. One large concavity and two smaller ones characterize the SOI-307-100 flame profile, due to the different flame speed previously described. Explosions causing knock often appear in close connection with a negative curvature in the flame front propagation profile. The presence of this negative curvature is associated with the slowdown of main flame front propagation and to low-temperature chemical kinetics in the zone not yet reached by normal combustion. Indeed, it was found out that the location of self-ignitions is strongly related to the curvature of the propagating flame front. This process can be deeply analyzed by evaluating the spatial evolution of the center of mass weighted on the luminous intensity (centroid of luminosity). Figure 2.4 illustrates the movement of the centroid from the spark plug position for one of the three analyzed conditions, SOI-307 cycle n°57. The centroid of luminosity starts moving slowly, and it remains located near the spark plug position. A slow deviation can be observed toward the exhaust or intake valves for all the test cases, reflecting the previously described prevalent flame front propagation directions. This shift can be partially masked by the carbonaceous deposits on the window.

Fig. 2.3 Comparison between flame outline before explosion and knock onset location in the end-gas region, for three selected test cases



The spectroscopic measurements have allowed to characterize the flame evolution with high spatial and temporal resolution and to detect other species present during self-ignition, knock phase, and involved in pollutants formation. Several species involved in the first exothermic reactions due to the self-ignition of the air-fuel mixture can be detected by means of spectroscopic and ultraviolet (UV) [16]. Simultaneous use of spectral emissivity and absorption measurements in UV-visible range have shown to be a powerful tool comparing with high-speed imaging techniques. In fact, the ultraviolet spectrum is important because of the presence in this region of the well-known “water bands” due to OH radical that contributes to oxidation of fuel, knock marker [17], formation of NO_x [17], and oxidation of soot [18]. CH and C_2 bands provide a more precise signature of the reaction zone. CH can be used as an indicator of temperature in flame studies and C_2 as a CH precursor or precursor of soot [19]. Finally, CH/OH ratio intensity can be employed as a measure of the local equivalence ratio [20, 21], whereas CN radical emission can be considered as the marker of spark discharge in the combustion chamber [22, 23]. Moreover, carbonaceous material and large aromatic molecules exhibit absorption bands between 200 and 350 nm [9, 16, 19, 24, 25].

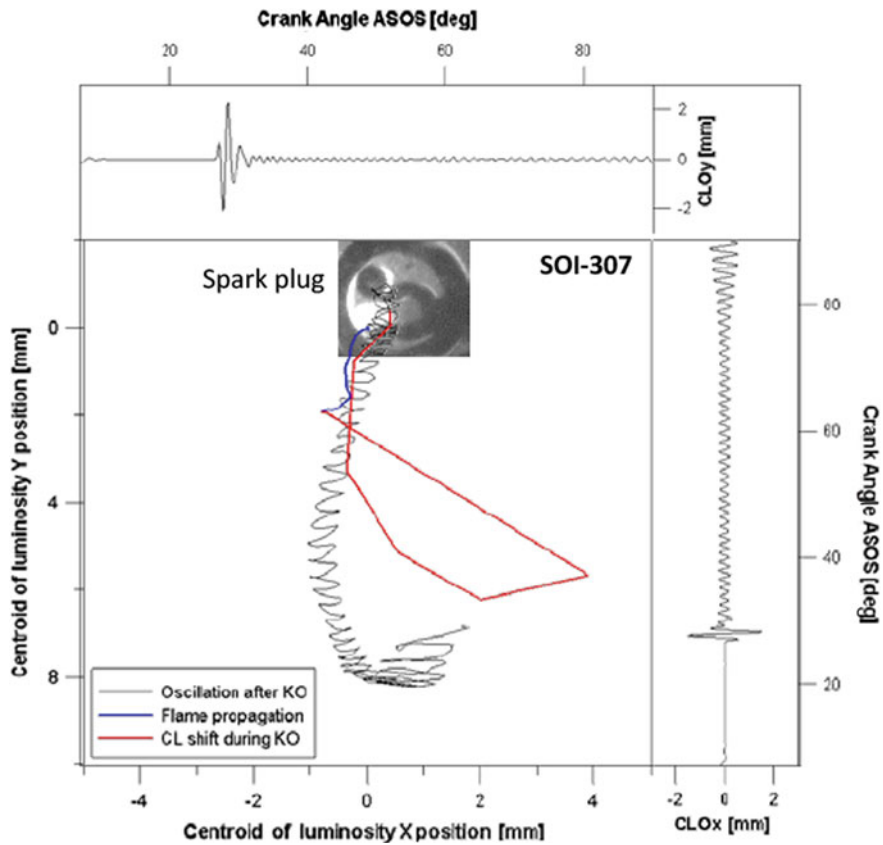


Fig. 2.4 Movement of centroid of luminosity evaluated for the test case SOI-307

2.4 Pollutants Formation

The luminosity/chemiluminescence imaging and the simultaneous planar imaging of laser-induced incandescence (LII) and elastic scattering have contributed to detect the onset of soot during the range of time in which a solid particle is formed from fuel molecules. The experimental difficulties involved in the soot formation and oxidation processes in the environment of the cylinder are enormous due to the high temperatures and pressures that extremely condition the reactive intermediate species occurring. Nevertheless, the light extinction, Rayleigh and Mie scattering, laser-induced incandescence (LII), and laser-induced fluorescence (LIF) allowed to follow the soot formation and oxidation process in terms of soot particle size and number density, as well as to have information on the flame temperature and the concentration of some typical species produced during the combustion process. As

an example, NO concentration and its temporal evolution can be obtained by both absorption and LIF measurements, which involves closely linked advantages and disadvantages.

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