operating conditions. Hereby not under consideration are, however, losses through exhaust gas treatment measures (lean NO_x trap regeneration).

Clearly recognizable is the great potential of controlled autoignition, in which, despite smaller basic potential from the standpoint of the perfect engine, extremely minute combustion losses, relatively small wall heat losses, and very minimal gas exchange losses lead to a high net indicated efficiency. This is obviously higher than that of variable valve lift control and only narrowly below that of direct injection, spray-guided combustion.

In the case of the hydrogen engine, the high compression ratio and above all the high air-fuel equivalence ratio ($\lambda > 3$) due to the extremely wide ignition boundaries of hydrogen have a very favorable effect on the basic potential of the perfect efficiency. The efficiency of the perfect engine amounts to about 56%. Combustion with an optimal position does reduce combustion losses. However, clearly higher wall heat losses also result from the higher combustion temperatures in hydrogen combustion, which destroys a large part of its potential. Nevertheless, a comparatively high indicated efficiency results.

It can be concluded from the above analysis that short combustion duration, resulting small combustion duration loss will cause higher wall heat losses. In this case, a compromise has to be found in order to be able to realize low fuel consumption. The same is valid for the relation between a higher compression ratio for the sake of a higher efficiency of the ideal engine and wall heat losses.

3.3 Optical Diagnostic Techniques

3.3.1 Introduction

Optical techniques have been developed to the point that they can be applied to institutional engine development. The following tables give a listing of various optical techniques and their potential applications in engine development. There are numerous methods applied in engine and combustion research, however, just a few of them have the potential of being applied in practical engine development.

This section gives an overview of optical methods and their application to various aspects of combustion analysis. The focus is on describing optical techniques which were found to be useful in supporting pre- and series development of IC engine combustion systems. The decision for application of a specific optical technique is always based on requested information and the efforts and chances to gain the required results with a given method. Consequently, the methods which have proven their benefits for combustion system development are easy to use and yield specific insight into relevant development tasks.

3.3.2 Optical Methods: An Overview

Tables 3.3–3.7 summarize fields of application, basic features of optical sensors, self-radiating in-cylinder objects which are accessible with passive optics and others which require external light sources for illumination. Some laser based techniques suitable for engine specific analysis tasks are given in Table 3.8.

Table 3.3 In-cylinder optical techniques – the tasks

Field of application	Task	Priority	Optical technique
Research	Understand combustion events	Scientific precision	Specific method and boundary conditions are defined by research task
Methods development	Comparison/ verification with simulation	Precise definition and description of test conditions	
Combustion system development	Testing of specific development variants	Realistic and relevant engine operation	Must comply with required engine operation, effort / benefit economy

Table 3.4 Basic features of optical sensors

Signal	Sensor	Time sequence	Temporal resolution	Spatial resolution
Image	Camera	Single shot and high speed camera	Shutter speed or illumination pulse	Pixel resolution via imaging
Radiation	Single- and multichannel sensors	Continuous	Bandwidth of signal converter and digitalization rate	Integral along aperture cone, or integral surface spot per channel

Table 3.5 Signal sources for passive optical techniques

Signal source	Object	Engine	Application
Radiating gas	Flame front, burned gas	SI engines	Flame kernel formation, flame propagation
Hot particles	Soot radiation	Diesel and GDI engines	Diffusion flame identification flame interactions in diesel engines, soot temperature, soot concentration
Hot surfaces	Surface radiation	Engine components	Component surface temperature

Table 3.6 Illuminated in-cylinder objects

Object	Illumination	Application
Fueal spray	Continuous or flash lamp	Spray propagation
Fuel wall film		Piston, liner, cylinder head surface
Deposits		Injector, valves, any surface
Engine components		Component functionality

Table 3.7 Laser based in-cylinder analysis techniques, Lackner (2008)

Method	Object	Information	Sensors
PIV, particle image velocimetry	Seeding particles, fuel droplets	Flow field	Camera
LDA, laser doppler anemomentry	Particles, droplets	Local flow velocity	Photodiode, multiplier
PDA, phase doppler anemometry	Droplets	Droplet size	Photodiode, multiplier
LIF, laser induced fluorescence	Fluorescent molecules	Species concentration	Camera
LII, laser induced incandescence	Soot particles	Soot distribution	Camera
Raman scattering	Molecules	Concentration, temperature	Multiplier
Light absorption	Molecules, particles	Concentration	Photodiode, multiplier

Table 3.8 Optical analysis methods in transparent research engines and in standard engines

Method	(DI) SI engine	(DI) Diesel engine	Sensors
Single cylinder transparent engine	Mixture formation, flame quality	Spray propagation, flame distribution	Camera
Endoscopic imaging in standard engine	Spray – combustion chamber interaction Diffusion flames	 Flame distribution	Endoscope and camera
Two color method in standard engine		Flame temperature, soot concentration	Front optic elements and optical fibers
Flame measurement techniques in standard SI engines	Mixture quality evaluation on basis of flame radiation		Single and multichannel fiber optical sensors

3.3.3 Application Examples of Optical Methods

This article presents the following measurement techniques:

- Imaging techniques to support combustion system development for Diesel and SI engines. Mixture formation and combustion analysis in transparent engines
- Imaging techniques with endoscopic access to the combustion chamber
- Flame radiation measurement in Diesel engines, signal evaluation with two color method
- Flame radiation measurement in SI engines

These methods' applications for SI and Diesel engine development are summarized in Table 3.8.

3.3.4 Diesel Engines

The image arrangement in Fig. 3.35 shows an ideal positioning for fuel spray, vapor cloud and diesel flame within the boundaries of a combustion chamber bowl.

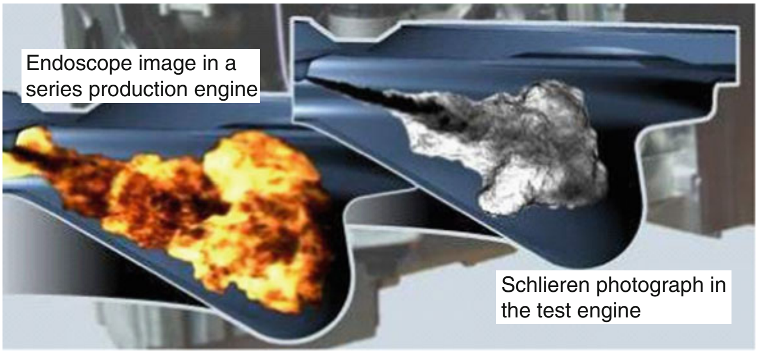


Fig. 3.35 Image arrangements: Diesel spray with fuel vapor cloud and Diesel flame inside the cross section of a combustion chamber bowl

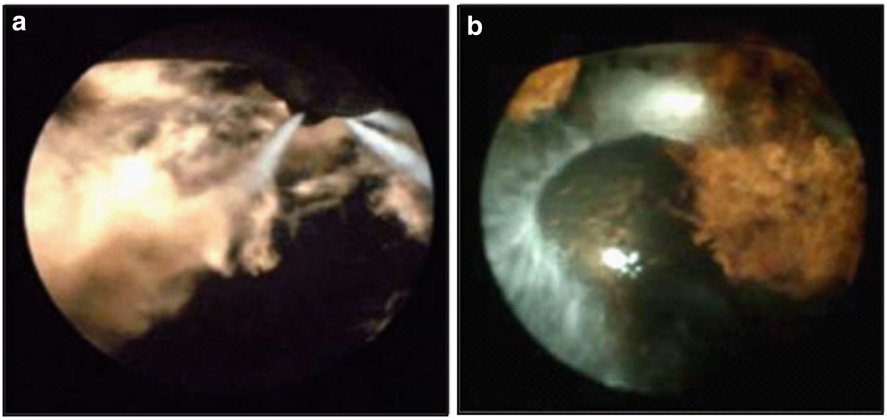


Fig. 3.36 Diesel fuel sprays and flame in warm engine (**a**), fuel wall film and flames in cold engine (**b**)

The Schlieren image shows the spray "core" near the nozzle hole as well as the wide field of the fuel vapor cloud. Such fuel vapor is formed as fuel droplets are heated by the compressed in-cylinder air and ongoing heat transfer finally results in ignition and flame formation, Winklhofer et al. (1992).

The second part of this image arrangement shows the diesel flame. The boundary drawings have been selected to suggest best use of available space without flames touching the head or piston surface.

Such ideal conditions are unattainable in real engine operation. At high load, flames always impinge on combustion chamber walls, in the cold engine at start and in the warm up phase, fuel droplets impact on the piston surface and may result in massive wall film formation. Examples for both cases are given in the endoscope images of Fig. 3.36.

3.3.4.1 Endoscopic Combustion Chamber Inspection

Endoscopes are optical instruments for image transfer by means of long, rod-shaped lenses or by coherent optical fiber bundles. In an engine, the endoscope accesses the combustion chamber via optical windows. Such combustion chamber windows are designed to withstand the pressure and temperature conditions of usual engine operating modes. With adequate design and material selection, window applications include full load operation in both Diesel and gasoline engines. Examples for an endoscope, window design and assembly in an engine are given in Fig. 3.37.

3.3.4.2 Combustion Chamber Imaging via Piston Windows in Research Engines

In combustion engine research and pre-series development there is growing need for combustion chamber inspection via transparent piston configurations. A large piston window allows simultaneous inspection of all fuel sprays as well as observation of the entire flame field as accessed by the window. Spray to spray and flame to flame uniformity are especially of interest in Diesel combustion studies. Figure 3.38 shows examples for Diesel flames, Lindstrom private communication. As optical access in such engines is provided by large windows and mirrors, such configurations are well suited to accommodate various optical and laser optical analysis techniques.

Radiation of a Diesel flame essentially results from thermal radiation of the soot particles formed under heterogeneous diffusion combustion of the fuel sprays. Spectrum and intensity of this radiating cloud of soot particles are used to evaluate soot particle concentration as well as their temperature. In a most simplified method, this evaluation is achieved with measurement of flame radiation intensity

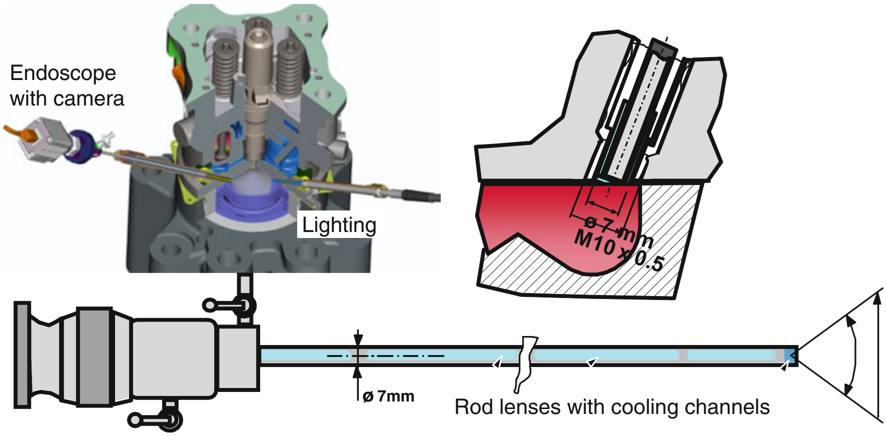


Fig. 3.37 Endoscope and endoscope insertion in the cylinder head of a Diesel engine

Fig. 3.38 Flame distribution seen through the piston of an optical research engine, Lindstrom private communication

within two narrow band spectral regimes and comparison of the spectral signals with Planck's radiation formula. This "two color" method was applied to gain the results presented in Fig. 3.40.

3.3.4.3 Flame Image Evaluation Examples

Flame position and propagation versus crank angle are the primary information provided by Diesel flame imaging. Evaluation of a Diesel flame's spectral brightness yields flame temperature and concentration of the soot particles contributing the flame radiation. Such spectral image evaluation is achieved with the two color flame analysis method, Gstrein (1987).

Diesel Flame Spectrum

Diesel flames are so called diffusion flames with remarkably high radiation intensity. Their spectral content is dominated by the thermal radiation of the soot particles present in the Diesel flame. A flame spectrum given in Fig. 3.39 shows this broad band thermal radiation together with the low intensity narrow band UV emission lines from OH radiation. In presence of such strong thermal diffusion flame radiation, any further narrow band molecular radiation is scarcely noticeable, Kuwahara and Ando (2000).

Soot Formation: Soot Oxidation Variants Analysis

Figure 3.40 gives a comparison of flame evaluation results which were derived from flame images recorded with an endoscope in a heavy duty (HD) Diesel engine. Combustion modes were under the influence of EGR and needle opening pressure, both of which have influence on engine out soot emission levels. The two color flame evaluation procedure is applied to an area of interest as shown in the flame photograph. Total visible soot concentration within this area is given for an entire

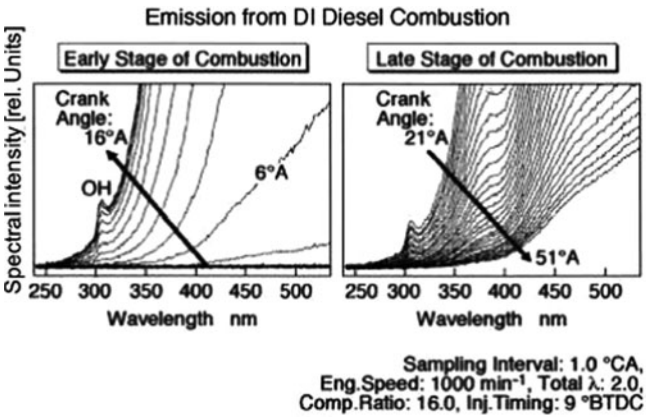


Fig. 3.39 Spectrum of a Diesel flame from early to late combustion. Narrow band OH molecular radiation and intensiv thermal radiation of soot particles, Kuwahara and Ando (2000)

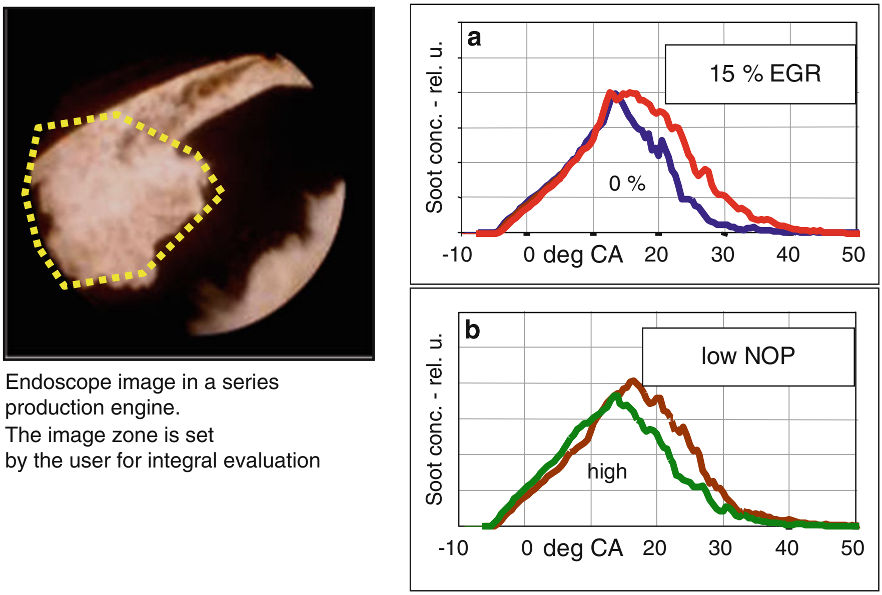


Fig. 3.40 Integral flame evaluation in area of interest: Soot bildup and soot oxidation at EGR variation (**a**) and at variation of needle opening pressure NOP (**b**)

set of crank angle resolved flame images. Consequently, the soot concentration graphs in Fig. 3.40 comprise the input from a few hundred individual flame images taken at consecutive cycles under stationary engine operating conditions.

The results given in the graphs of Fig. 3.40a, b show the steady rise of soot concentration up to a maximum at about the time of end of injection. The following decrease of the soot concentration signals reflects soot oxidation.

This oxidation process reflects the influence of the engine operating variants. With EGR, soot oxidation slows down and results in the well known soot emissions tradeoff. Raising nozzle opening pressure results in faster soot formation, but also in a more effective soot burn-off after end of injection.

In the late expansion stroke, soot particles are either oxidized or they are too cold to maintain sufficient signal intensity for endoscopic imaging. The comparison of soot emission levels with in cylinder soot radiation signals recorded throughout the late expansion stroke shows significant correlation of both signal sets. Such comparisons confirm the suitability of the method relating relative in-cylinder soot signals with absolute engine out emission levels.

Soot Evaluation with the Two Color Method

Diesel engine emissions development requires ever growing attention to transient operation. Engine start and gear change and tip in transients are main contributions to engine out soot and NOx emissions. This defines the task for identification of cylinders and cycles which are predominant in contributing to overall emissions.

Figure 3.41 gives an example for a tip in test with conventional engine out soot opacity measurements. The graphs show a set of six repeated tip in tests (2,000 rpm, IMEP step from 3 to 19 bar) with a typical opacity maximum before the engine gains thermal equilibrium (A). One out of four cylinders was equipped for integral two color flame measurement. Signal evaluation provides a relative soot number for each cycles ["V-soot" signal, Winklhofer et al. (2006)]. At constant load, the signal traces in Fig. 3.41b show noticeably higher fluctuations than the opacity signal, at the tip in it immediately responds to the load change event and it shows peak V-soot numbers slightly ahead of the steady state high load mode.

One out of four cylinders was equipped for integral two color flame measurement. Signal evaluation provides a relative soot number for each cycle ["V-soot" signal, Winklhofer et al. (2006)]. At constant load, the signal traces in Fig. 3.41b show noticeably higher fluctuations than the opacity signal, at the tip in it immediately responds to the load change event and it shows peak V-soot numbers slightly ahead of the steady state high load mode.

Such comparison first of all shows the different features of engine out opacity and in-cylinder flame measurements. In the opacity meter, the sample gas arrives at the sensor position after passing through the exhaust manifold and the instrument tubing and it comprises a gas mix of all cylinders. The opacity instrument time resolution is 0.1 s.

The in-cylinder flame measurement avoids these time delay and cylinder mixing effects. The V-soot (or V-NOx) data are available for each individual cycle of the cylinder of interest. Crank angle resolved flame temperature and soot concentration data are accessible for refined analysis and flame interpretation.

Deriving recommendations for engine development or actuator calibration from such signal traces requires separation of general trends from sporadic combustion events. This is achieved with repetitive test runs and signal evaluation for average trends and sporadic events. The mean cycle test diagram in Fig. 3.41c shows

- The immediate response of enhanced soot formation at tip in
- The peaking of soot formation in the high load cycles before the engine has achieved its high load thermal equilibrium

3.3.5 SI Engines Optical Diagnostics

In a gasoline engine the ideal situation shows fully vaporized fuel which, at stoichiometric concentration, is homogenously mixed with air and residual gas. The spark plug discharge ignites this mixture, it forms a flame kernel that progressively consumes the unburned charge under turbulent diffusion of the flame front

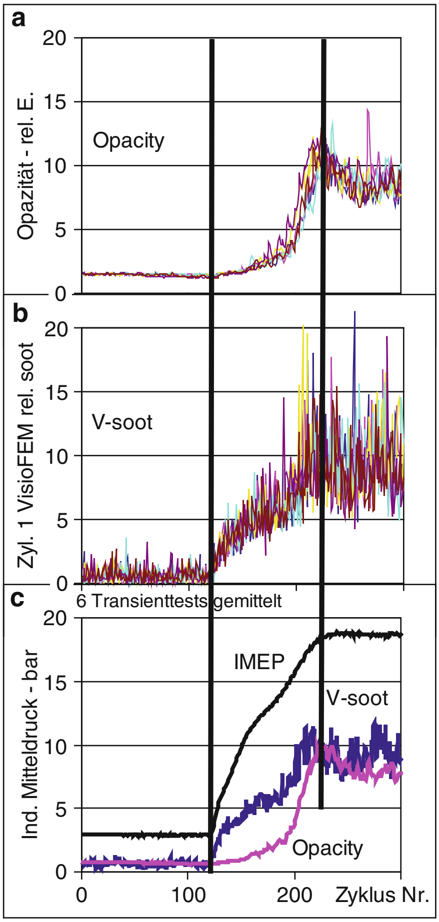


Fig. 3.41 Soot formation in a tip-in test. The two color V-soot signal shows cylinder and cycle specific soot peaks. (**a** and **b**) test repetitions, (**c**) test ensemble average

constituents. Mixture homogenization ensures combustion to be free of soot formation. Stoichiometric conditions yield burned gas temperature near the adiabatic bulk gas limit of around 2,400 K. Such gas conditions, together with three way catalysis are prerequisite for a low emissions engine.

Combustion system development must ensure that mixture formation procedures finally yield such fully vaporized fuel which is homogenously mixed with air or which provides well defined stratified mixture to burn under highest possible thermodynamic efficiency.

Optical analysis techniques support such development work to achieve targets for:

1. Emissions: mixture formation for soot free combustion in port injection and direct injection systems
2. Stability: flame kernel formation, flame front propagation under influence of turbulent in-cylinder flow
3. Efficiency: knock initiation site analysis
4. Irregular combustion: engines with high power density combustion systems are under risk of uncontrolled self-ignition events. Such irregular ignition and combustion is identified with optical diagnostic procedures
5. Non-contact surface temperature measurement: the use of infrared sensitive signal converters extends optical sensing techniques for thermal radiation evaluation, Winklhofer et al. (2009)

Emissions: evaluate mixture formation quality by means of flame radiation analysis

3.3.5.1 Turbulent Flame Propagation in Premixed Charge

In ideally premixed charge, flame propagation is driven by the diffusion of the flame front constituents into the unburned charge. This flame front propagation is under the influence of turbulent and large scale gas flow. Activation energy to support the combustion process is provided by the heat exchange between combustion products and unburned gas, thus the chain reaction to support ongoing combustion is maintained until all available charge is converted into products.

The main part of reaction enthalpy is released by oxidation processes within the flame front. This results in the build up of cylinder pressure. In simultaneous events, the radiative recombination of molecules generated by the oxidation process contributes to flame luminosity.

Consequently, in such premixed flames, heat release due to combustion and flame radiation is pseudo simultaneous events. Comparison of the rate of heat release with flame radiation intensity thus yields information on how well the mixing process achieved premixed charge, see Fig. 3.42a for a typical signal example with good mixture preparation.

The primary mechanism for flame propagation is molecular diffusion. In homogeneous charge engines, this results in isotropic flame propagation. Such isotropic

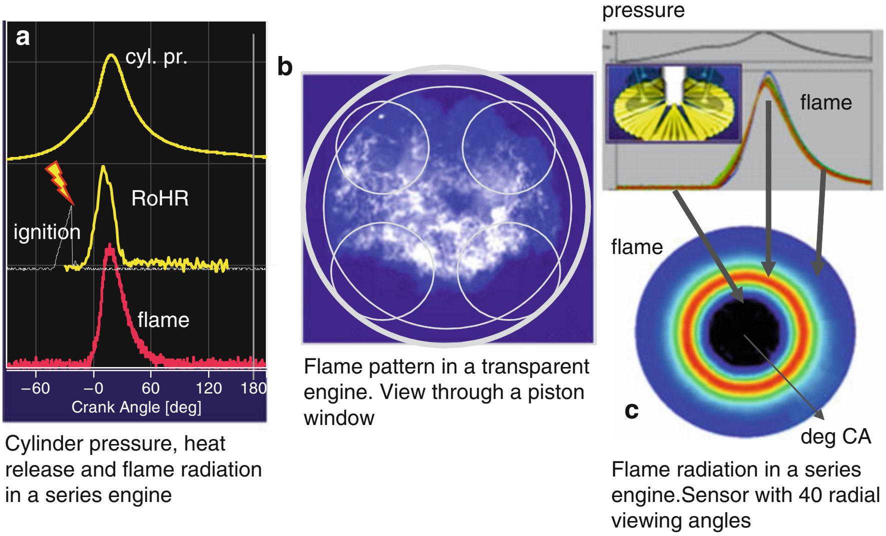


Fig. 3.42 Premixed combustion (**a**): simultaneous heat release and flame radiation. (**b**): flame front under influence of turbulent gas motion. (**c**): isotropic signature of flame pattern signals at premixed combustion

propagation is enhanced by the motion of the fluid. Local flow vortices result in turbulent flame front distortions and any macroscopic flow in the overall convective motion of the expanding flame. The flame photograph in Fig. 3.42b shows such turbulent flame front structure as well as the drift of the flame towards the combustion chamber exhaust side.

Measurement of flame radiation within the narrow apertures of multichannel fiber optic sensors provides a simple and informative technique to check for premixed combustion. An isotropic premixed flame yields highly similar flame radiation signals along individual sensor apertures. The graphics in Fig. 3.42c show the similarity of the multichannel signals. Flame consistency is evident in the polar plot of the flame radiation signals. Highest flame radiation intensity is coincident with the peak rate of heat release.

3.3.5.2 Flame Radiation in Heterogeneous Mixture

Even with incomplete fuel evaporation, combustion essentially starts with a premixed flame kernel which expands into the fuel air mixture near the spark plug. As such premixed flame gets in contact with fuel droplets or with fuel wall films, these rich mixture regimes start to burn under diffusion (sooting) conditions. The flame photograph of Fig. 3.43b shows such heterogeneous flame patterns with fuel droplet combustion (sooting flame).

The resultant flame radiation time traces show the early coincidence of premixed flame radiation and heat release. As fuel rich regimes ignite and burn under sooting conditions, their radiation surpasses the premixed flame in both radiation intensity and duration, see Fig. 3.43a.

The rich mixture is mostly concentrated in specific locations, so diffusion flames are highly localized. This becomes evident in flame images, as well as in multi-channel flame radiation measurements. The signal patterns in Fig. 3.43c give evidence of wall film combustion throughout the expansion stroke near one intake valve of a PFI engine. Combustion pressure traces again show that such diffusion combustion has a negligible contribution to heat release despite high light intensity .

3.3.5.3 Applications of Flame Analysis Techniques

The examples in Figs. 3.42 and 3.43 show flame images or flame radiation signals to be well suited to identify combustion going on under ideal premixed conditions, or to understand that rich mixture gives rise to diffusion flames with the risk of incomplete combustion. As such diffusion flames are the source for soot formation, identification of such events is helpful to improve mixture formation for low soot combustion. The benefit of identifying soot formation with in-cylinder measurements is seen in the ability of evaluating individual cylinders and cycles contributing to engine out emissions. This is especially useful under emissions relevant engine start and transient operation.

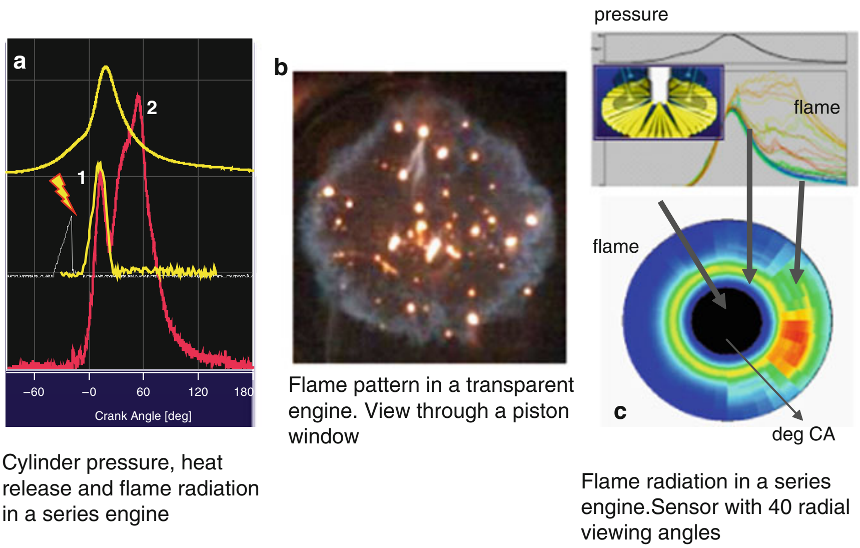


Fig. 3.43 Premixed and diffusion flames (**a**): premixed flame 1: with simultaneous heat release and flame radiation. Diffusion flame 2: high flame radiation intensity at negligible heat release. (**b**): rich mixture (droplets, wall film) is ignited by premixed flame. (**c**): flame pattern signals, diffusion flames result in highly anistropic flame signature

3.3.5.4 Test Examples

Acceleration

Especially in GDI engines, a fast tip-in transient (from part load to full load) can result in pronounced soot emissions as in-cylinder wall temperature is insufficient to evaporate the sudden increase of injected fuel. Calibration of such transient modes requires test iterations to best adjust injection parameters for acceptable soot emissions. Exhaust gas measurements, however, are just capable of evaluating the overall engine emissions behavior. Contributions from individual cylinders or specific cycles are smeared with engine out or tailpipe measurements. Such precise cycle by cycle evaluation for each individual cylinder is achieved with flame radiation measurements.

Combustion signal records for cylinder pressure, rate of heat release and flame radiation intensity are given in Fig. 3.44. Fuel storage effects at a tip-in event become evident in the crank angle resolved flame signals before the combustion chamber temperature becomes sufficiently high to evaporate all injected fuel for premixed combustion.

Adjustment of fuel injection parameters such as injection timing and pressure yields significant reduction of such fuel storage effects, see Fig. 3.44b.

Engine Start

Starting an engine requires injection of excess fuel to compensate for partial evaporation in the low temperature engine environment. The evaporated fuel fraction is expected to result in near stoichiometric, ignitable mixture, whereas the excess fuel forms wall films and just marginally contributes to combustion. Such conditions result in diffusion flames and soot emissions. Suitable selection of fuel injection parameters must avoid misfire cycles and minimize the time required to achieve low emissions premixed combustion. Such mixture and flame conditions are well suited for analysis with the flame radiation measurement techniques of Figs. 3.42–3.44.

In case of misfire cycles, there is the need to understand the root causes in order to compensate fuel injection for either lean or rich misfire events.

The examples of Fig. 3.45 have been recorded in one cylinder of a four-cylinder engine. Pressure and rate of heat release signals show three misfire cycles before the onset of successful ignition combustion. The flame signals show the absence of any flame activity in cycle nr. 1. The following cycle shows flame activity, however without any noticeable heat release. In cycle 3, there is flame activity from the early compression stroke onwards. Here, obviously, combustion residuals from cycle 2 have ignited the fresh charge. These misfire and irregular combustion cycles are then followed by regular combustion. With this signal sequence for cylinder pressure, heat release and flame radiation, it is concluded that overfuelling was the primary cause for the misfire and irregular combustion events.

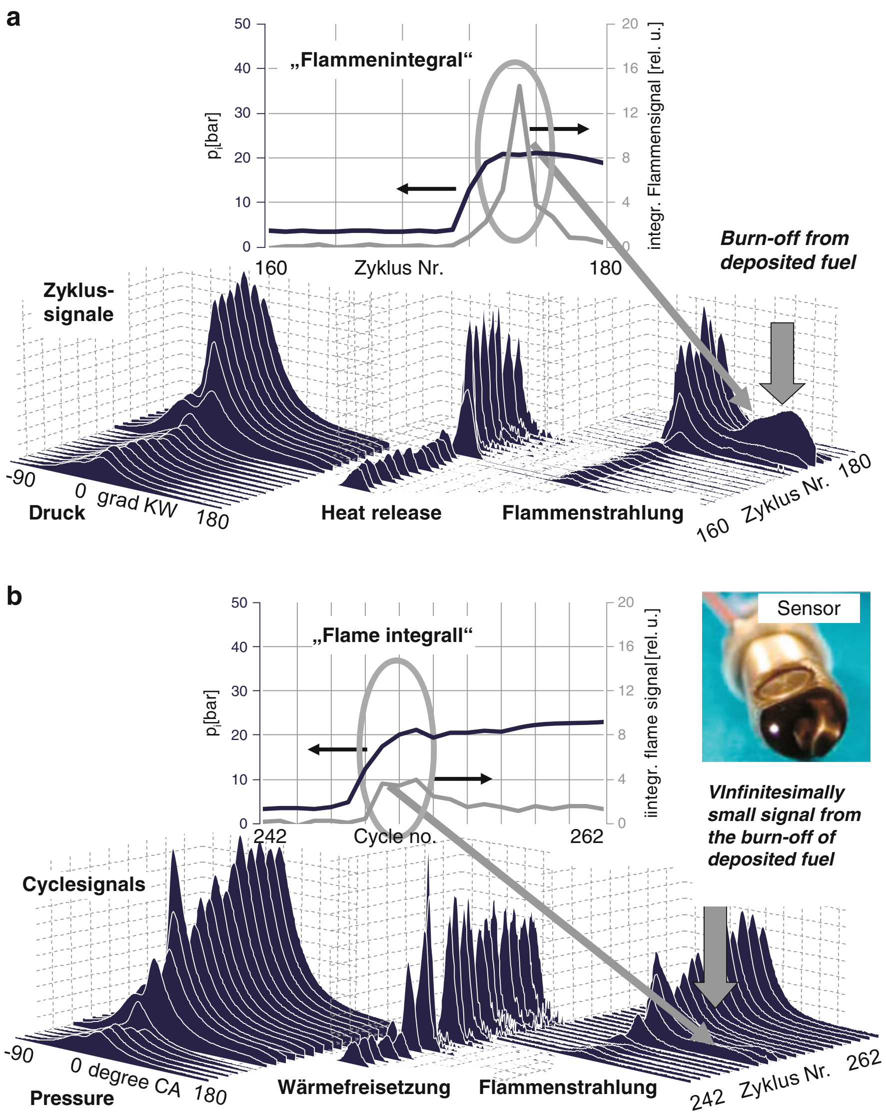


Fig. 3.44 Soot formation at tip-in: (**a**): rich flame is seen by its flame radiation peak in expansion stroke. (**b**): improved fuel evaporation avoids high diffusion flame peaks

Verification of Flame Signals for Soot Evaluation

The above examples have shown that flame intensity signals recorded with a broadband (200–1,100 nm) photodiode provide a simple crank angle trace to identify premixed as well as diffusion flame combustion. Signal comparisons,

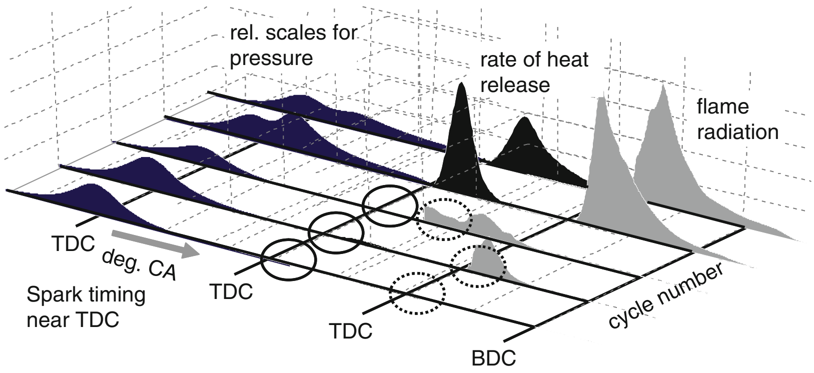


Fig. 3.45 Misfire cycles at engine start. Heat release together with flame radiation signals enable identification of root causes

furthermore, show the large intensity contribution from diffusion combustion. Thus, a simple integration of the flame intensity signal for an entire engine cycle yields a cycle specific number to describe subsequent combustion events. Under stationary operating conditions, this cycle integral flame signal is compared with engine out soot emissions. Emissions trends for particulate mass as well as particulate number counts in Fig. 3.46 confirm the usefulness of this simple cycle integral number to identify combustion cycles with significant contributions to engine out soot emissions. It must be noted that this cycle integral number is to serve as an identifier of combustion cycles with noticeable diffusion flames, it is not capable of substituting any engine out particulate measurement technique.

Local Diffusion Flame Information

Fiber optic spark plugs with sensor channels arranged for circumferential flame detection have already been shown in Figs. 3.42 and 3.43 for the evaluation of symmetric or non-symmetric flame patterns in a PFI engine test. Flame evaluation examples for a GDI engine are given in Fig. 3.47. Injector operating conditions yield specific distribution patterns of resultant diffusion flames.

Combustion Stability: Flow Field, EGR, Lambda

In engine development, combustion stability is defined by the coefficient of variation of $IMEP_H$ (CoV_{IMEPH}) with an evaluation of bulk combustion duration (10–90%) and flame formation period (spark −10%)with crank angle timing of characteristic integral heat release percentages (T10%, T50%, T90%). In many cases, the primary reason for insufficient stability is found in an elongated ignition and flame kernel formation phase. As this flame formation phase is susceptible to

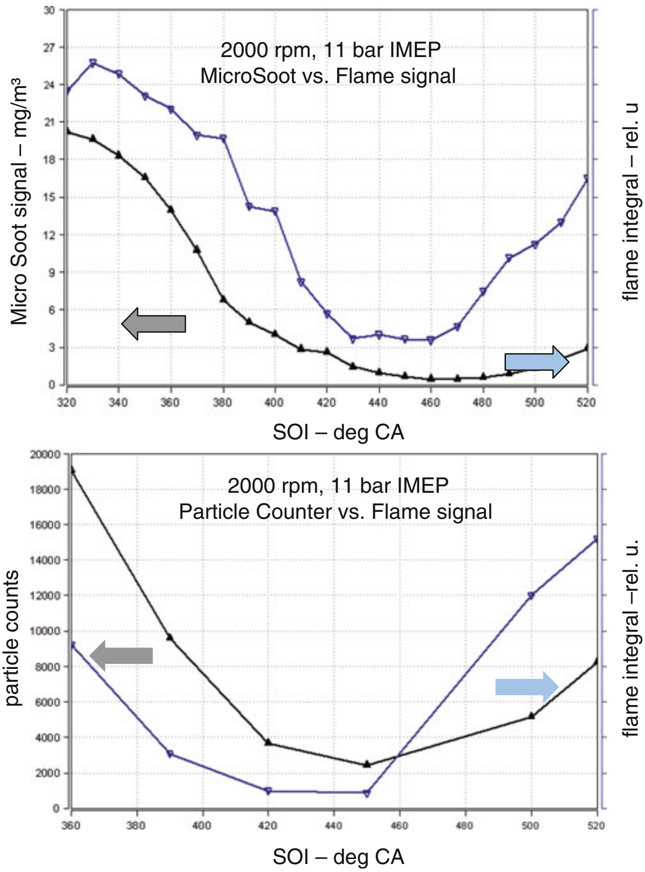


Fig. 3.46 Trend comparison: emissions data at stationary engine operation (particulate mass and number count) compared with cycle integral flame radiation signals

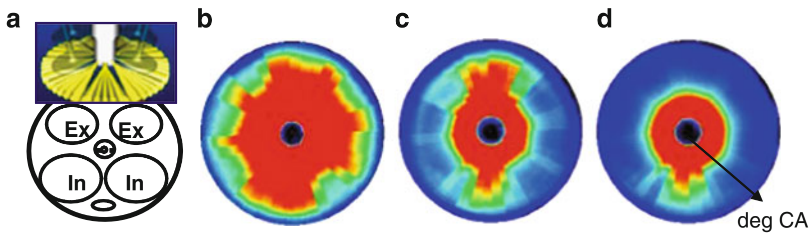


Fig. 3.47 Flame pattern signals in a GDI engine (**a**): sensor configuration, (**b**): injection early, sooting combustion of piston wall film, (**c**): late injection results in diffusion flame near liner, (**d**): best calibration with residual diffusion flames underneath injector

variations of local flow field, and mixture and residual gas concentrations, there is need for measurement techniques suited to identify any of these parameters. Methods and sensors suited for such measurement in either standard or in optical research engines are given in Table 3.9.

Table 3.9 Measurement tasks and methods to evaluate combustion fluctuation root causes

Measurement task	Method	Sensor	Reference
Lambda	HC, narrow band absorption	Spark plug with absorption path, spark emission spectroscopy	Hall and Matthews (2002), Berg et al. (2006), Fansler et al. (2002)
Flow field, turbulence	LDA	Spark plug with LDA optics	Ikeda et al. (2000)
EGR	CO_2 absorption	Spark plug with absorption path	Berg et al. (2006)
Flame propagation	Flame radiation, light barriers	Fiber optic spark plug sensor, ion probe head gasket	Witze et al. (1997), Winklhofer and Salzinger (2004)
Heat release	Cylinder pressure	Pressure sensor	
Flame kernel	Flame photography	Transparent engine endoscope	

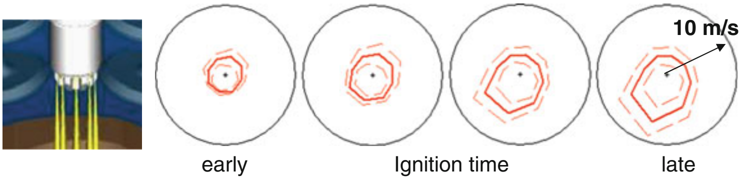


Fig. 3.48 Flame kernel propagation, cycle average (n = 100) and standard deviation at spark advance variation

An example for flame kernel propagation measurements is given in Fig. 3.48. The polar diagrams show the radial flame velocity components as the flame kernel moves through the individual channel apertures of the fiber optic spark plug. As the flame kernel expands under the influence of the local flow and gas concentration, variation of this environment is reflected in the flame kernel velocity components. At constant spark timing, the flame kernel fluctuations are shown by their RMS values. With the variation of spark timing, the polar components give evidence for the flame kernel's response to flow and turbulence.

Combustion Efficiency: Knock Center Detection

An engine's compression ratio (CR) is selected to allow most efficient combustion for a given fuel quality under myriad speeds and loads. This results in full load operation to compromise with spark timing in order to limit knocking pressure amplitudes. As such spark advance limitation has influence on combustion efficiency, power density, combustion noise, engine durability and driveability, there is considerable effort put into the exploitation of an engine's knock limit. Optical flame analysis techniques support these development efforts with detection of knock center distribution and a root cause analysis of spark advance limitations.

Knocking combustion is the result of end gas auto-ignition. After regular ignition, the flame requires a few 10's of deg CA to propagate through the combustion chamber and consume the fuel air mixture. Throughout this combustion phase, the temperature of the unburned gas rises in response to the pressure rise from compression and combustion. This isentropic heating can result in thermal auto-ignition of the unburned mixture. Endgas self-ignition can be avoided if flame propagation is sufficiently fast, and if endgas time-temperature history is limited. Combustion system development must provide measures to enhance flame propagation into critical areas and it must avoid overheating of endgas regimes. Such development efforts are supported with measurement of flame propagation and with identification of self-ignition centers.

Measurement methods for the detection of auto-ignition sites must fulfill requirements as listed in Table 3.10. This is essentially met with techniques which detect in-cylinder gas signals and provide location of the knock signal origin (Mazoyer et al. (2003), Wytrykus, Düsterwald (2001), Philipp et al. (1995), Philipp et al. (2001)). The spontaneous nature of a self-ignition event and the high propagation velocity must be accounted for with adequate signal recording techniques.

For practical measurement applications, multi channel optical spark plug sensors have found wide acceptance for knock center measurement in passenger car engines. They are replacing standard spark plugs without any further need for special engine adaptation. A signal example together with the basics for identifying knock center location is given in Fig. 3.49.

Auto-ignition occurs in endgas areas. Figure 3.50 shows how retarded flame propagation allows formation of endgas areas which eventually give rise to auto-ignition whenever thermochemical reactions have sufficient time to trigger exothermal chemical kinetics.

Table 3.10 Topics and measurement demands for knock center determination

Topic	Feature
Engine operation	Spark advance at knock limit
Knock event at which time?	Spontaneously in a time window close after pressure peak
Gas response to self-ignition	– Pressure wave is started by spontaneous self-ignition – Pressure wave is linked to gas density wave – Density wave is linked to brightness wave in luminous burned gas
Sensor signal pressure	Local pressure acting on surface of sensor
Sensor signal light	Brightness signal recorded within (volume) aperture field of sensor
Signal duration	PRESSURE (density, luminosity) wave transit time across combustion chamber: 50–200 μs
Velocity of knocking pressure wave	Sound velocity in hot compressed gas: up to 1,000 m/s at full load
Required measurement sensitivity	Knock center location at knock amplitudes larger than 0.5 bar
Optical measurement system task	Find origin of propagating brightness wave
Alternative method pressure	Find origin of propagating pressure wave
Acoustic oscillation in combustion chamber	Form after reflection of primary wave front

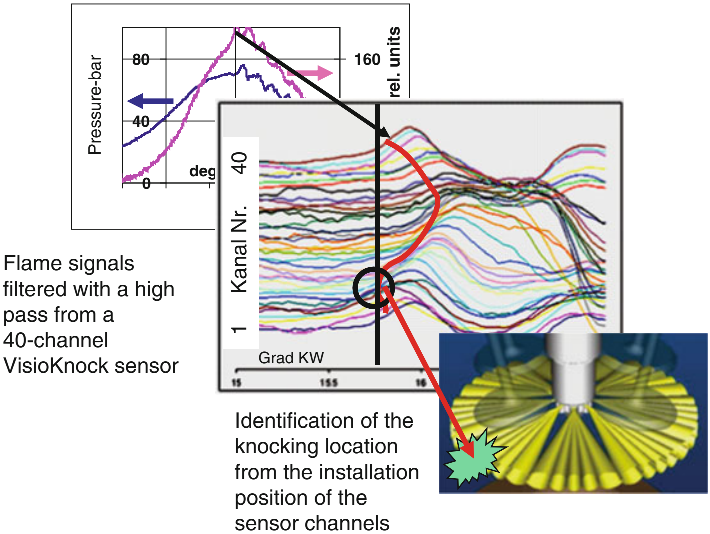
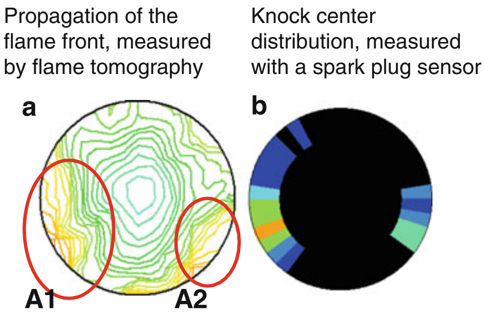


Fig. 3.49 Knock center measurement in a standard multicylinder engine with a VisioKnock spark plug sensor

Fig. 3.50 Position of endgas areas A1, A2 and corresponding knock center distribution



The steps and benefits achieved in a systematic combustion development project are summarized in the engine performance plot of Fig. 3.51. The initial engine configuration had a full load limit with significant knock center agglomeration on the exhaust side. Modification of in-cylinder air motion provided enhanced flame propagation towards the exhaust side and resulted in effective endgas burn-off in those critical areas. This enhanced flame propagation allowed a significant advance of spark timing. The resultant full load line provided BMEP improvements of up to 1 bar.

3.3.5.5 In-cylinder Self-Oscillation

Knocking combustion, first of all, is recognized by its ringing noise. This ringing noise signature is a result of acoustic resonance excited by the auto-ignition event and enhanced by pressure wave reflection at the combustion chamber walls.

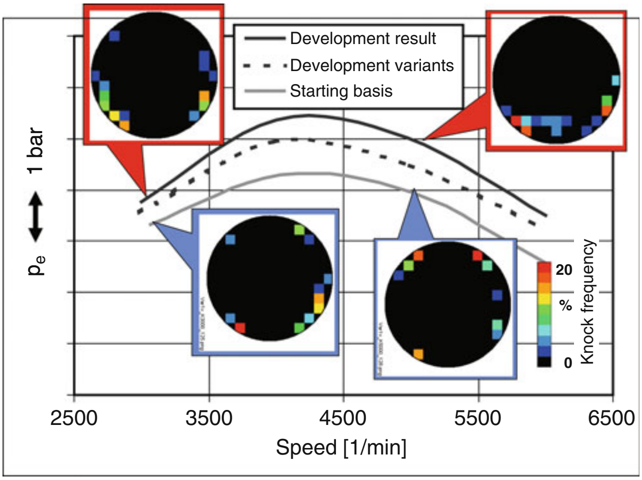


Fig. 3.51 Engine development for knock limit improvement. Basis: knock centers at exhaust side limit spark advance. Final variant: knock centers at intake side enable significant BMEP improvement

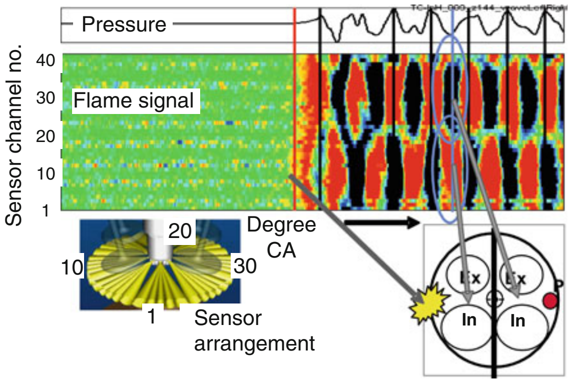


Fig. 3.52 High pass filtered signals of cylinder pressure and flame radiation. The flame signals show the pressure (= brightness) wave with ongoing reflections and excitation of a resonant frequency. P: position of pressure sensor

As optical sensor arrays provide measurement of brightness signals in the entire combustion chamber, the signal patterns show the acoustic field of the in-cylinder gas oscillations. The signal example in Fig. 3.52 shows the modulation of the gas brightness field as started by the self-ignition event and enhanced and filtered by ongoing reflection of the oscillating gas.

Irregular Combustion

Increasing the efficiency and power density of gasoline engines can result in operating conditions which come into the risk of thermochemical activation of uncontrolled pre-ignition. Ignition time and location are no more under the control of engine electronics. In case of pre-ignition at full load fuelling, such “irregular ignition” can result in pressure amplitudes that are large enough to cause mechanical damage.

Reducing this risk requires measurement techniques which are capable of identifying the locations of such irregular ignition and eventually to understand and avoid their root causes. Table 3.11 gives an overview of potential causes and engine conditions which bear the risk to transition into such undesirable behavior.

The task for combustion engineers is to detect cycles and cycle sequences with irregular combustion events and to use flame sensor arrays which enable localization of irregular ignition origins. Sensors and instrument configurations capable of meeting these requirements are shown in Fig. 3.53 and described in more detail in Winklhofer et al. (2005). Figure 3.54 gives an example for signal traces recorded in an irregular combustion cycle and evaluation of the self-ignition center.

Non-contact Temperature Measurement

Optical sensors and endoscopes are as capable of transmitting near infrared thermal radiation. Thus, together with IR sensitive photodiodes or cameras the optical systems can be extended for measurement of in-cylinder or exhaust system components’ temperatures. Calibration procedures account for the geometric sensor to object arrangement and provide measurement accuracy of around 10 K in normal

Table 3.11 Topics and metrological requirements for irregular ignition and combustion

Potential root cause	Engine operating mode	Initiating irregular ignition	Engine development action
Hot spot	High load operation	Load increment	Local cooling
Glowing deposits	Part load – full load sequences	Spontaneously after deposits buildup, after normal knocking combustion	Avoid fuel and oil deposit formation
Knock to irregular ignition transition	Engine at knock limit	Increased heat transfer to all surfaces under knocking combustion	Reduce knock limit, improve local cooling
HCCI ignition	Low engine speed, hot engine start	High load limit, engine start calibration, residual gas scavenging	
Residual gas and lambda fluctuations	High load	Following a misfire cycle	Avoid misfire cycles
Regular ignition/irregular combustion	High load	Regular ignition followed by very fast combustion	Turbulence, mixture composition and temperature

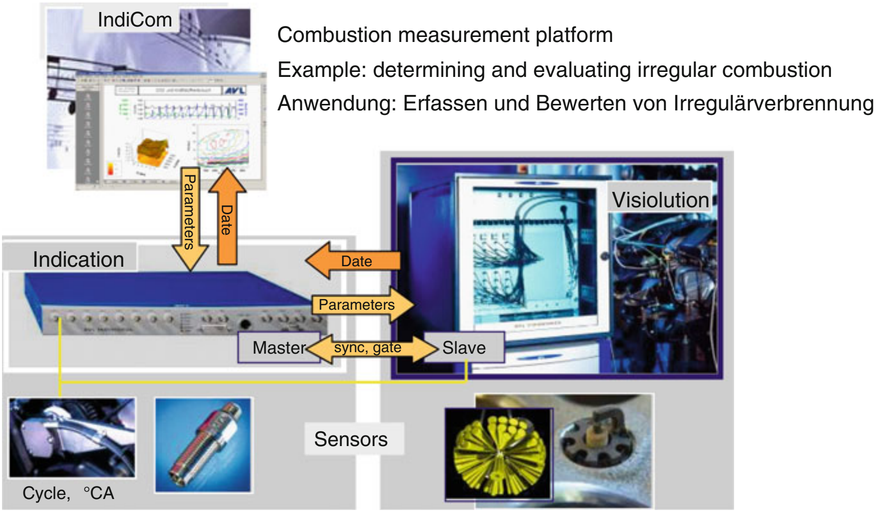


Fig. 3.53 Modules of a "combustion measurement platform" for the recording of spontaneous, irregular combustion events

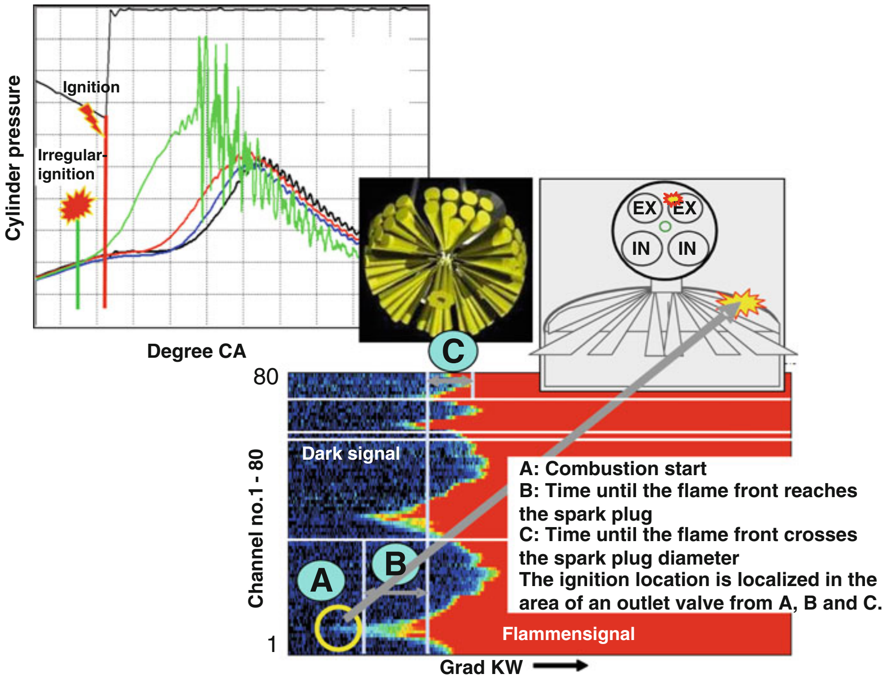


Fig. 3.54 Signal example shows location of irregular ignition

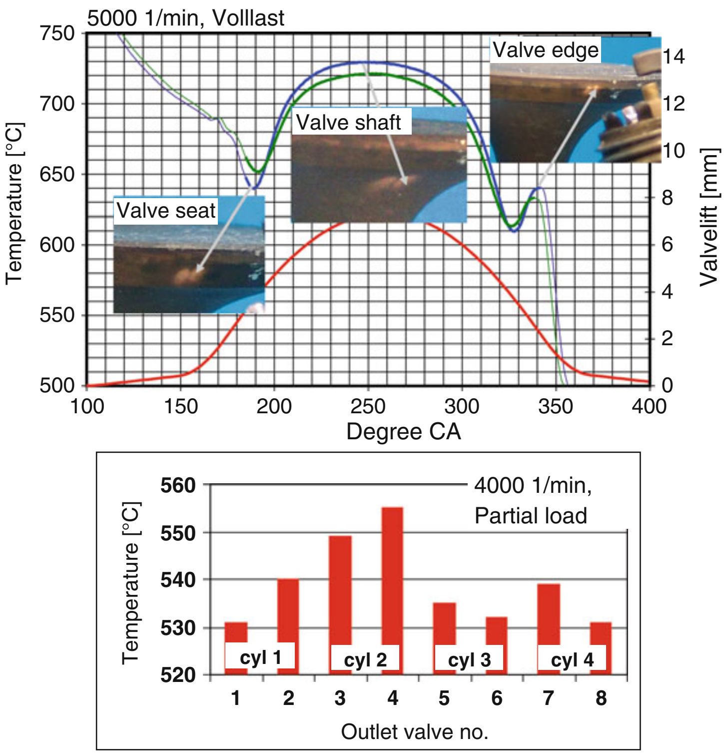


Fig. 3.55 Exhaust valve temperature measurement is accomplished with evaluation of thermal valve radiation

test bed operation, Winklhofer et al. (2009). An example for exhaust valve measurements in a four cylinder engine is given in Fig. 3.55.

3.3.6 Laser Based Measurement Techniques

Table 3.7 has listed a number of laser based measurement techniques to be used for local or planar in-cylinder diagnostics. To enable their application in engines, some of these techniques need large sized optical windows in transparent engine configurations to access the combustion chamber and to enable the use of optical receivers and cameras for signal detection.

In research applications, laser optic effects are exploited for measurement of velocity, concentration and temperature of gases and fuel droplets. Laser absorption techniques are used for soot concentration measurement, Lackner (2008).

An example supporting development of mixture formation processes in direct injection gasoline engines is given in Fig. 3.56. Laser induced visualization of fuel

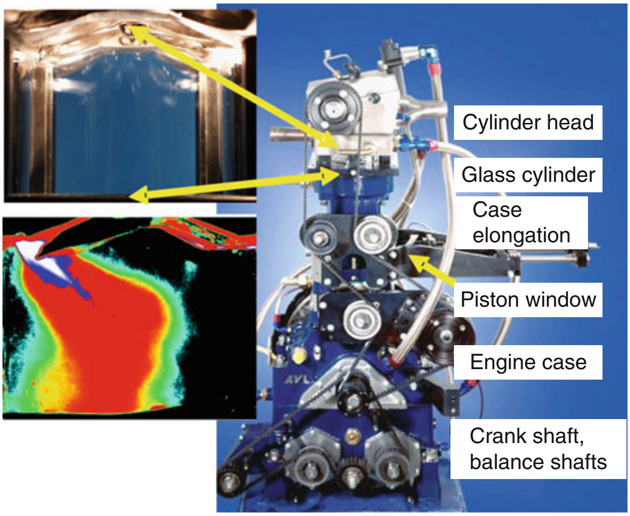


Fig. 3.56 Transparent single cylinder engine with large size windows (glass cylinder and window in piston) provides access for laser diagnostic techniques. Example shows fuel mixture cloud in a GDI engine. Fuel droplets and vapor are visualized by means of laser induced fluorescence (LIF)

spray and vapor distribution enables selection of injectors and their operating modes best suited to meet injection and mixing requirements for premixed combustion. As such imaging is accomplished under real engine flow and geometry conditions, it has become part of industrial engine development procedures, Fuchs et al. (2009).

3.3.7 Optical Combustion Diagnostics: Status and Forecast

Sensor access into the combustion chamber together with straightforward signals interpretation are considered to be the key elements for a successful application of optical diagnostic techniques in IC engine combustion system development. Sensors, signal recorders and results interpretation must interface with the engine test environment and complement conventional analysis techniques while providing otherwise unattainable information. Specific analysis tasks result from requirements to provide relevant insight and decisions to improve mixture formation, combustion as well as exhaust aftertreatment processes.

The features of any diagnostic system must enable standardization of routine analysis procedures. Expanding applications and meeting yet undefined requirements must be provided for with adequate interfaces. This is best accomplished with modularity of sensors, signal converters, recorders and memory. Such modularity is made available within the IC engine "combustion measurement platform".

On this platform, specific measurement tasks are fulfilled with dedicated modules. The platform itself

- Enables synchronized data recording of modular components
- Handles trigger signals between modules
- Provides master-slave signal recording logics
- Provides the user interface to access local data and results

An example of such modular system configuration for the measurement and analysis of irregular combustion events has been shown in Fig. 3.53.

The tasks required from practical combustion diagnostics start with standard thermodynamic analysis, they comprise emissions formation issues related to fuel injection, flame behavior as well as functionality of exhaust aftertreatment systems. Analysis of such combustion and emissions related tasks is further extended into the fields of durability and robustness of combustion related components as fuel efficient engines march the closer exploitation of theoretical engine operation limits while meeting ever more stringent emissions regulations.

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