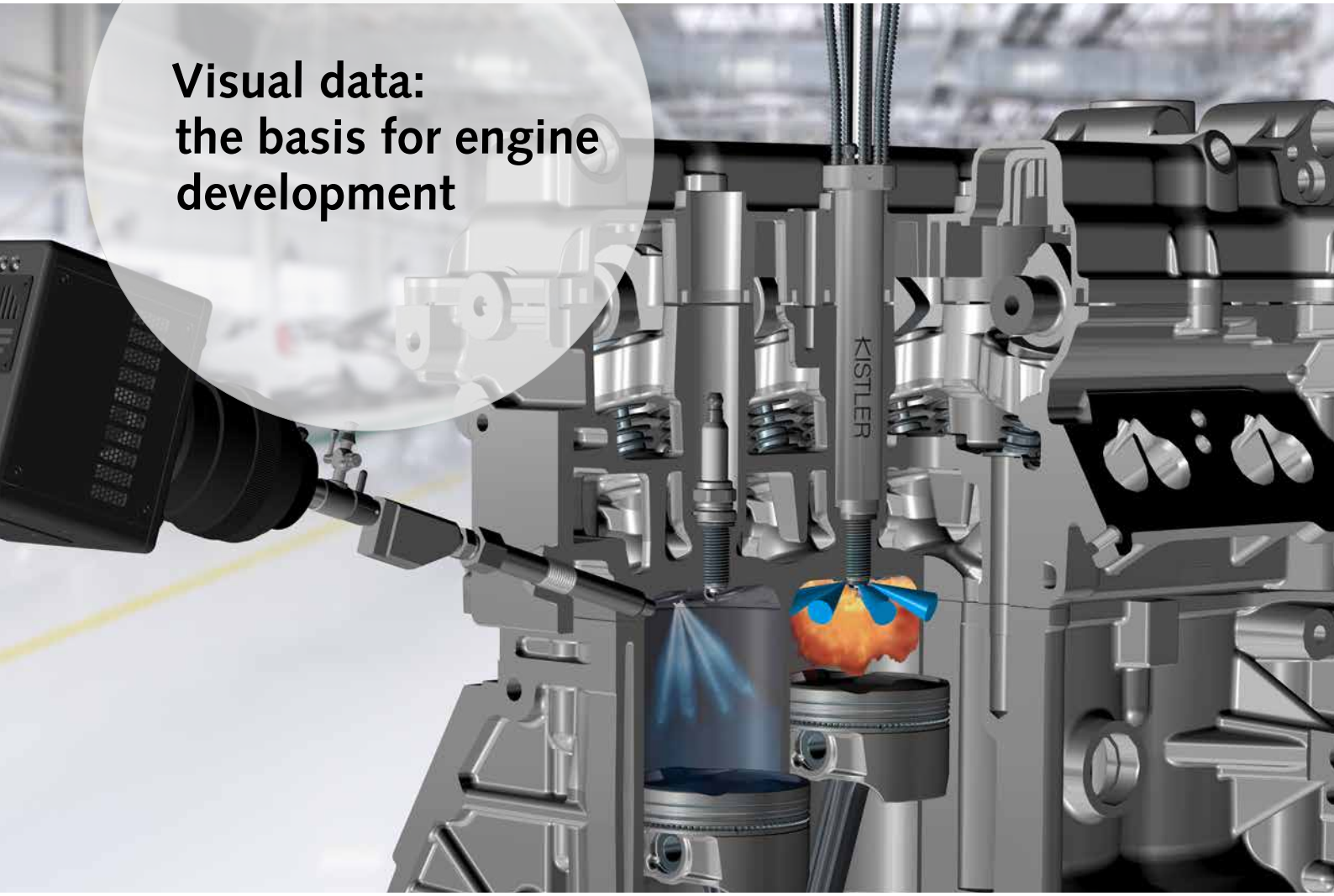
KISTLER

measure. analyze. innovate.

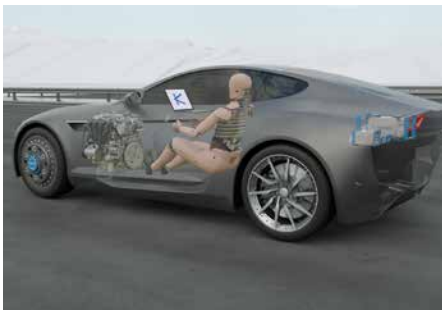


Optical combustion analysis

Accurately understanding and optimizing processes in the combustion chamber

Absolute Attention for tomorrow's world

Kistler develops solutions for challenges in measurement technology with a portfolio that comprises sensors, electronics, systems and services. We push the frontiers of physics in fields such as emission reduction, quality control, mobility and vehicle safety: our products deliver top performance to meet the standards of tomorrow's world, providing the ideal basis for Industry 4.0. This is how we pave the way for innovation and growth – for our customers, and with our customers.



Kistler: the byword for advances in engine monitoring, vehicle safety and vehicle dynamics. Our products deliver data that plays a key part in developing efficient vehicles for tomorrow's world.

Measurement technology from Kistler ensures top performance in sport diagnostics, traffic data acquisition, cutting force analysis and many other applications where absolutely reliable measurements are required despite extreme conditions.

By supporting all the stages in networked, digitalized production, Kistler's systems maximize process efficiency and cost-effectiveness in the smart factories of the next generation.

Editorial

Although much attention is currently devoted to electromobility, the combustion engine continues to evolve: quieter and more efficient units with lower levels of pollutant emissions are constantly being developed and made ready for series production. The method of combustion analysis based on cylinder pressure measurement has been established for decades, and has been perfected during that period. In the meantime, combustion analysis using optical methods has developed into a valuable complementary technology. Increasingly powerful optoelectronic equipment now plays a significant part in generating critical impetus for engine development, with the focus on perfecting mixture formation and the combustion process. This overview of products and solutions from Kistler shows you what is already possible – today's developers benefit from additional visual information that is the basis for acquiring extensive knowledge about events inside the engine. The range of different approaches and technologies reflects the huge variety of opportunities for development in this field. Read on to discover how ongoing innovations in this measurement technology are opening up new potential.

Contents

Schematic view of the high-speed camera system used to visualize the injection jet on a gasoline engine with direct injection

Understanding precisely what's happening in the combustion chamber

Alongside engine indication based on measurements of cylinder pressure, Kistler's expertise includes various other measuring techniques that help to optimize the combustion process. Methods for optical combustion analysis give development engineers additional resources for increasing an engine's efficiency.

Kistler offers customers a vast range of different technologies based on visual investigation of the combustion process in the cylinder. In most cases, the luminosity of the combustion is used as the key indicator – depending on the composition of the gas, the wavelength of the emitted light varies significantly.

Identifying and preventing unwanted effects
The different measurement methods are equally suitable for compression-ignition (CI) engine concepts and those with spark ignition (SI); depending on the purpose of the investigation, various combinations are both possible and appropriate (see page 13 of this brochure for more details). In a CI engine, the wavelengths are typically within the range that is visible to the human eye; in a SI engine, on the other hand, they reach the ultraviolet range.

Visualization and optical analysis can provide a precise understanding of the processes in the combustion chamber, such as flame propagation. Undesirable effects such as knocking, pre-ignition and soot formation can be visualized and traced back to their causes. The knowledge gained can be used to boost efficiency and reduce emissions – to mention just two examples.

Everything from one single source
Kistler supplies the entire measuring chain, from optics and data acquisition through to software for evaluation. Customers also benefit from all the engineering services they require in the course of their projects. The focus here is on minimizing the integration effort and on obtaining measurement results that can be quickly utilized.

Benefits of optical combustion analysis from Kistler
- Visualization of the entire processes in the combustion chamber
- Spatial and time-based visualization of processes such as injection, flame propagation, knocking, soot formation and pre-ignition
- A precise understanding of the combustion process is the key to optimizing it
- Measurement technologies can be combined flexibly depending on the purpose of the investigation
- One single source for the entire measuring chain, from sensors to data analysis
- Comprehensive advice, on-site service and flexible support with measurement campaigns

Just as flexible as your application

In response to advances in combustion engine development, optical measurement methods are increasingly used to gain a more accurate picture of processes in the combustion chamber. Kistler offers its customers a varied range of technologies for developing suitable combustion processes, increasing efficiency levels and reducing emissions.

Open a viewing window onto the combustion chamber
Fiber-optic measuring spark plugs offer a practical way to gain rapid insights into the combustion process. Standard spark plugs are used as the technology carriers – very little effort is required to equip them with optical probes. This creates a window onto the combustion chamber that allows precise analyses based on visualization of the combustion process.

Combined cylinder pressure measurement and optical analysis
The combination of cylinder pressure measurement and optical analysis quickly provides information about critical engine parameters. Unique technology from Kistler allows optimization of the combustion process with minimal outlay of time and money: an ideal way to obtain a deep understanding of processes in the combustion chamber.

Visualizing processes inside the engine
Imaging processes supply additional knowledge that helps users to interpret injection behavior and flame propagation. The cameras used for this purpose make phenomena such as pre-ignition and soot formation visible. Customers can choose from a varied range of camera technologies, borescopes, optical probes and image intensifiers to match each specific development task.

Solution	Application and objectives	Benefits
Optical measuring spark plug 	• Captures the radiation given off by combustion as light intensity • Spatial and time-based visualization of knocking, soot formation and pre-ignition	• Up to 16 optical probes in one spark plug • Can be integrated into all commonly used serial spark plugs • Viewing direction can be selected freely
Multi-measuring spark plug 	• Combination of cylinder pressure measurement and optical analysis • Spatial and time-based visualization of knocking, soot formation and pre-ignition	• Integrated, compact and rugged design with no need for an additional measuring bore • 8 optical probes in one spark plug • Integrated miniature cylinder pressure sensor (3 mm) • Visualization of the entire processes in the combustion chamber
Global optical measuring technique 	• Integration of total radiation with one optical probe • Can be used in SI and CI engines • Determination of soot temperature and soot intensity	• Compact, rugged design • Reduced scope of measurement equipment to detect soot
High-speed imaging system 	• Imaging measurement technology to visualize the combustion process • Optical analysis of injection behavior, flame propagation, pre-ignition and soot formation	• High-speed camera with exposure time of up to 1 µs • Can be extended with an LED illumination system • Can be extended with a light intensifier

Optimizing processes inside the engine

How can processes in the combustion chamber be visualized – with minimum outlay of time and money – to obtain valuable information that can be used to optimize combustion? The solution from Kistler: fiber-optic spark plugs that convert the brightness patterns into usable data.

Any commonly used serial spark plug can be equipped with up to 16 optical probes. These rugged probes measure the light intensity even at high pressures and temperatures, and their design ensures that the thermal characteristics of the entire system remain stable. The light signals are transferred to optoelectronic receivers via optical fibers, and are then converted into voltage signals.

The resultant measurement curves provide information about the quality of the combustion process. Flame kernel propagation and charge motion can be understood in detail – even during idling and cold starting. Phenomena such as knocking, pre-ignition and sooty combustion can easily be identified from the curve profiles.

Application areas
- Combustion analysis
- Flame kernel development
- Knock detection
- Detection of pre-ignition – Detection of soot formation

Overview of benefits
- Standard spark plugs can be equipped with up to 16 optical probes
- Viewing direction can be selected freely
- Very high resistance to extreme temperatures and pressures
- High measuring sensitivity and accuracy

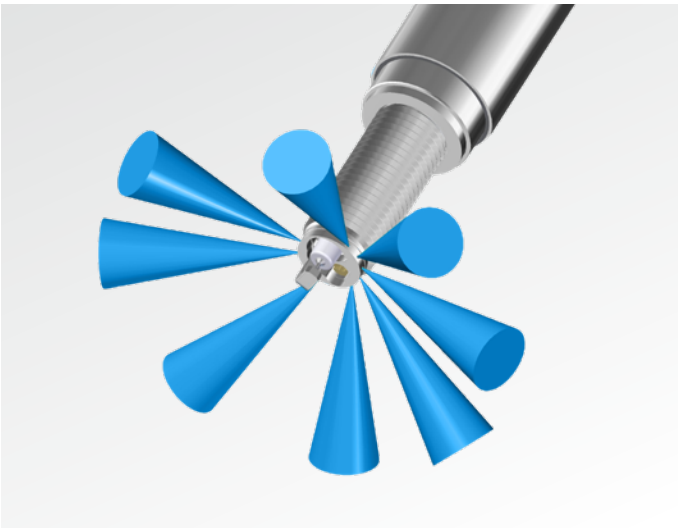
Spark plug with 8 radial optical windows

Boosting efficiency in development

The new multi-measuring spark plug from Kistler provides customers with a highly efficient tool. By combining pressure and light measurement technology in one compact, rugged product, Kistler makes it possible for engine developers to save time as well as money. This new measuring spark plug supplies a complete visualization of the entire processes in the combustion chamber – efficiently providing developers with the knowledge they need to optimize the combustion process.

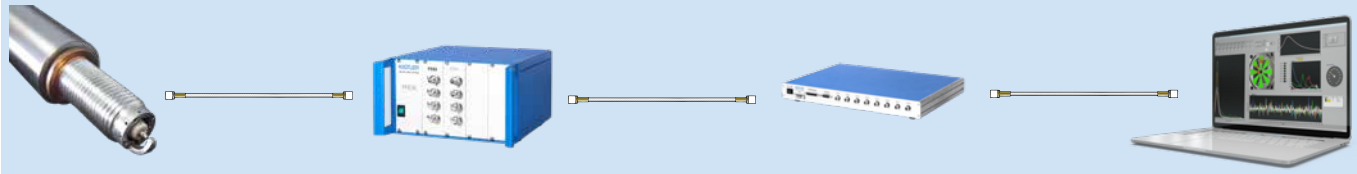
The flame radiation is measured optically and transmitted to the COMBI evaluation system via a light amplifier. The integrated software generates a graphic display of combustion quality, based on predefined parameters. Users benefit from precise insights, so they can reliably detect phenomena such as knocking, sooting combustion or pre-ignition.

Sapphire window for enhanced precision
The mounting bores for the optics are lined with special sapphire bars whose geometry determines the viewing direction and aperture angle. The optical windows are protected by a cover that allows even more precise definition of the viewing direction. It also prevents any uncontrolled entry of light, and falsification of the measurement due to "misguided light."



Benefits of the multi-measuring spark plug
- Cylinder pressure measurement and optical combustion analysis combined in one product
- Integrated, compact and rugged design with no need for an additional measuring bore
- Eight optical windows onto the combustion chamber (radial and/or axial directions of observation)
- Integrated miniature cylinder pressure sensor (3 mm)
- Various thread sizes, heat values, spark positions and electrode spacings are possible

Fiber-optic spark plug – FOSP



Serial spark plug with built-in optical windows

Amplifier system: PMD

Combined acquisition of measurement data

Software-based analysis of measurement data

Global optical measuring technique

The global optical measuring technique (or GMT) has become established as a fast and efficient measurement methodology. It involves installing an optical probe in existing accesses to the engine, such as the glowplug bore in a CI engine.

Single probes to determine soot
Single probes have proven their merits for investigations of radiation where there is no requirement for spatial resolution. Thanks to the wide observation angle, radiation is captured across large areas of the combustion chamber and is then evaluated individually. In CI engines, soot concentration and temperatures can be determined and resolved over time with the help of an algorithm (two-color method). In SI engines, GMT is used to detect undesirable soot particles. If only one optical probe is used, the outlay on measurement equipment is reduced accordingly.

Benefits of the global optical measuring technique (GMT)
- Wide observation range inside the combustion chamber
- Easy integration (into existing engine accesses)
- Application in research engines and standard/series engines
- Simple to handle

Imaging processes deliver detailed insights

For both SI and CI engines, special camera systems can be used to obtain visual information about aspects such as injection and flame behavior.

For more in-depth optical investigations of the combustion process, Kistler offers cameras with various technologies that supply high-precision images from the combustion chamber.

High resolution for high-precision images
Cameras with cutting-edge chip technology are essential for spray analysis in particular. Because of their high resolution, these cameras capture even the smallest droplets to provide detailed information about the form and propagation of the injection process.

Plug-and-measure thanks to special software
Both low-speed and high-speed imaging systems from Kistler are delivered with specialized software for test stand use. Cylinder pressure data is acquired simultaneously with the sequence of images, and is available for a combined analysis. This eliminates the troublesome task of synchronizing different measurement techniques. Work proceeds rapidly thanks to flexible visualization and evaluation.

Characteristics and benefits of the system
- Optical combustion analysis system with a high-speed camera
- Illumination and image capture via the same access in the cylinder head
- Can be adapted to every engine with a borescope and optical probe
- 1-megapixel images at frame rates of up to 12,800 fps
- Minimum exposure time: 1 µs
- Can be extended with LED illumination system and cylinder pressure measurement

Get the full picture – in fractions of a second

Imaging systems from Kistler based on high-speed cameras capture changes in the combustion chamber at intervals of a few microseconds. Optical data obtained in this way can be combined with the pressure data as the basis for deducing numerous key values and parameters.

For this purpose, all the components in the measuring chain have been designed to operate under extreme ambient conditions. Borescopes and special optical probes can also be used to gain access under difficult conditions, or to access very compact combustion chambers (see next page).

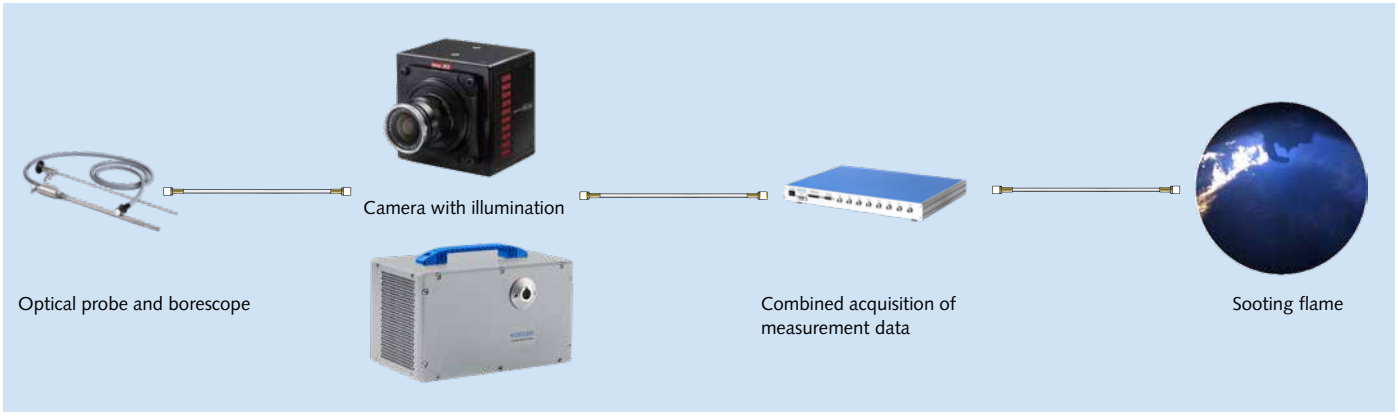
Including the UV spectrum in measurements
Other components such as a light intensifier can also convert UV light into visible light so that it can be included in the measurement. This is especially important for SI engines where part of the combustion process takes place in the UV spectrum.

High-performance evaluation electronics
COMBI provides customers with a high-performance system to evaluate measurements. Outstanding benefits include synchronous comparison of image data and cylinder pressure data for combined analyses. The flexible hardware starts with 8 channels and allows to add up to 64 channels. The matching PC software offers an extensive range of analyses with numerous parameters and flexible levels to suit all users, from beginners to experts.

The right camera is all-important
Measurement methods based on imaging can be used for an exceptionally wide range of applications and purposes. Kistler offers various cameras to meet these needs. Cameras are differentiated according to the system they use. Cameras with frame rates of more than 1 KHz are known as "high-speed cameras."

HIS – high-speed imaging system
Even more possibilities for imaging-based investigation of processes inside the engine are opened up when compact high-speed cameras are used in combination with minimally invasive technology from Kistler. High frame rates and storage rates allow recording of large numbers of complete combustion cycles. Investigations can be focused on stochastic events such as knocking, pre-ignition or uncontrolled combustion. Both the camera technology and the illumination have been modified to meet the higher requirements. High-power LEDs ensure that users benefit from perfect visibility.

Measuring chain for high-speed camera system



All-In-One probe for illumination and image capture, frontal diameter: 8.5 mm

Eyes open everywhere

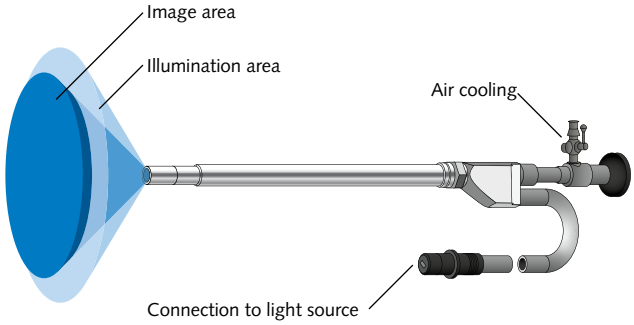
Borescopes and special optical probes from Kistler open up a viewing window into the combustion chamber – even when conditions are more difficult.

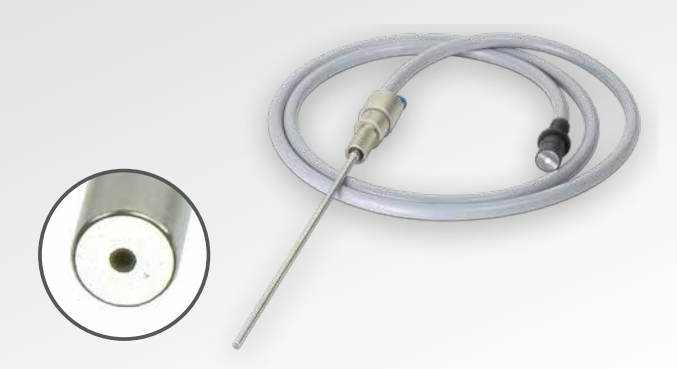
Every engine is different. This is why Kistler offers exactly the optical accessories that are needed to gain deeper insights and examine even the most compact combustion chambers. Optomechanical components from Kistler are developed for minimally invasive use, and are designed to withstand high temperatures and pressures.

Sensitive components such as borescopes are fitted with additional protective sapphire windows that shield them from pressure and temperature influences. They can be adapted flexibly to the specific application – both for standard borescopes and UV probes. The integration effort required is no more than for a cylinder pressure sensor.

Special systems to analyze injection behavior
Situations where the injection spray is to be recorded as well as the flame radiation require illumination probes to which a high-power light source must also be connected. The size and positioning of the illumination probe are critical factors for the quality of the captured images. Resistance to higher temperatures eliminates the need for air cooling. But if the probe is located at a distance from the cooling water channels in the cylinder head, air cooling is advisable.

Different optical probes are used depending on the cylinder diameter. In order to provide sufficient light, this is introduced via one, two or four coupling points.





Benefits of optomechanical systems from Kistler
- Minimally invasive technology
- Very compact design
- Heat-resistant thanks to temperature-resistant bonding and air cooling
- Extensive visual range in the combustion chamber
- Variable design according to the application (diameter, angled optics, etc.)

Benefits of the illumination system from Kistler
- Strong luminosity, up to 72,000 lm
- Complete adaptation with light guide and sapphire window
- LED is less safety-critical than lasers
- Long service lifetime, low maintenance
- Software control mode and intensity settings via Ethernet, or manually via keypad

Clear-sighted analyses

Direct insights – at no extra cost
The compact All-In-One probe from Kistler features another outstanding benefit: thanks to an innovative illumination concept, no additional access to the combustion chamber is now required. This complete system combines illumination and image capture in one compact structure – so integration outlay is reduced to the minimum. The light path is separate from the image path. This prevents reflections on the protective window of the borescope. Illumination is provided via a ring on the edge of the probe.

More light!
Imaging of highly dynamic processes requires extremely powerful illumination. A special LED light source from Kistler can be used for full illumination of the processes in the combustion chamber – such as the injection and spray formation – within just a few milliseconds.

The LED illumination system, with its three versions (P40, P80 and P160) is one of the most powerful light sources for industrial use that is available on the market. Unlike laser-based systems, it is not safety-critical and requires exceptionally little maintenance.

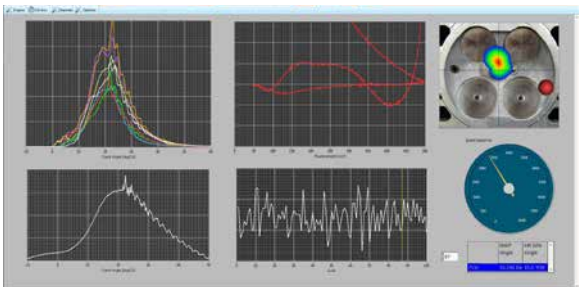
Continuous or pulsed high-power light modes
This solution was specifically developed for light-critical camera applications and high-speed imaging. The system can be used as a continuous or pulsed light source. In both applications, it offers high light output which can be increased even further in pulsed mode.

See and be seen

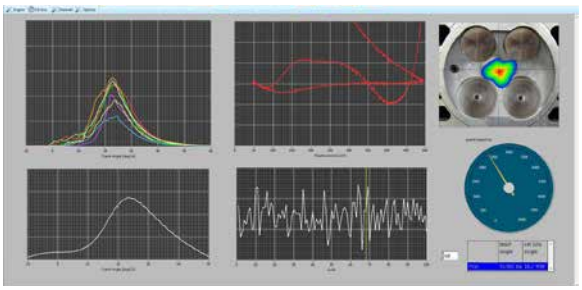
As well as providing a simple way to adapt the optical measuring spark plugs, this comprehensive acquisition software offers real-time visualization of the results. Changes to the engine operating condition are shown immediately on the user's screen as the result of the optical measurement. Data can be shown for the individual cycle, or as an average for consecutive cycles. This eliminates the need for laborious post-processing. Development engineers can run their test programs without interruptions – so valuable time is saved.

Measurement results available in real time
These three illustrations show just part of this powerful software. The alignments and observation volumes of the optical probes are entered in the software, and an image of the combustion chamber is stored. This allows online visualization of the formation of the flame kernel, the location of knocking onset or the soot intensity. For soot formation in the combustion chamber, a parameter (SRN – Soot Reference Number) is determined for each combustion cycle to allow quantitative assessment of the combustion process.

Benefits of the evaluation software
- Up to 64 measuring channels
- Results displayed in real time
- Key indicators for quantification are determined
- Intuitive, menu-prompted user interface



Knock location detection



Flame kernel formation

Soot detection

Best choices for developers

The measurement technology to be selected for each investigative goal requires careful consideration. The next table summarizes the purposes for which the methods described here are suitable. As well as consulting the table, ask Kistler's team of experienced engineers for advice on which measurement approach offers the best prospects of success for the purpose of your investigation and your development goal.

	FOSP	MMSP	GMT	HIS
	Fiber-optic spark plug	**Multi- measuring spark plug**	**Global measuring technique**	**High-speed imaging system**
Ignition timing	++	++		+
Spark propagation	•			++
Flame kernel formation	+	+		++
Flame propagation				+
Investigation of injection behavior				++
Knock detection (time-related)	++	++		•
Knock detection (spatial)	++	++		•
Detection of pre-ignition	++	+	+	+
Location of pre-ignition	+	+		+
Determination of soot intensity	+	+	++	•
Determination of soot temperature			++	•
Location of soot formation	+	+		++

++ very good results
+ above-average results
• usable results

Engineering support and Kistler expertise on site

Our service teams: fired by enthusiasm for your development project

Our service is just as flexible as our range of solutions: from advice on test stand setups to choosing the right equipment to assist with measurement campaigns, we make sure that you achieve optimum results from optical combustion analysis.

Optical combustion analysis is an innovative and complex measurement technology that requires expertise and detailed knowledge: it goes without saying that sound advice from our technical sales specialists is essential throughout all phases of a project. We work with our customers to examine what is feasible, and how we can support them with the best possible solution.

All-round engineering support
Kistler also offers its customers direct on-site support with commissioning and optimization: our services include adapting the required measurement technology to the specific engine as well as technical support with the setup on the test stand. For measuring campaigns, we also offer a loan service for individual measuring chain components such as electronic devices.

Measurement technology as a service
All the optical combustion analysis solutions described here can also be provided as a service. This is often the right approach – especially if the scope is still quite small, or if only individual units or features are to be examined. Kistler offers you the flexibility you want, with support tailored to your development task – simply contact us!

At our customers' service across the globe

Thanks to Kistler's global sales and service network, we are always close to our customers. Some 2,000 employees at more than 60 locations are dedicated to the development of new measurement solutions, and they offer customized on-site support for individual applications.

Find out more about our applications:
www.kistler.com/applications

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