Optomechanics

Optomechanical components for combustion analysis
Borescopes, optical probes and illumination

General
With precise knowledge of combustion processes, combustion behavior can be controlled so as to minimize undesirable phenomena such as knocking, pre-ignition and inefficient combustion. Optical investigations based on imaging techniques (such as the use of high-speed cameras) deliver informative and meaningful insights that are used (for example) as input for CFD calculations. Optomechanical components from Kistler are developed for minimally invasive use, and they are designed to withstand high temperatures and pressures. They only require small access bores into the combustion chamber; alternatively, existing accesses such as glow plug or cylinder pressure bores can be used.

Application areas:
- Spray propagation
- Spray form
- Flame propagation
- Pre-ignition
- Sooting combustion

Standard borescopes
Kistler has developed special borescopes for use in combustion engines. Their key features include compact design as well as heat resistance, and special care was taken to allow observation of the maximum possible area of the combustion chamber. Temperature-resistant bonding of the tips of the optical components enables them to withstand the high temperatures near the combustion chamber. Air cooling can be connected to the standard compressed air supply. Even with cooling, the borescopes require additional protection; this is provided by glass which shields the optics from the high temperatures and pressures during combustion.

Dimensions and characteristics:
- Diameter: 4.0 mm, 6.5 mm, 8.0 mm
- Length: 300 mm
- Transmission wavelength range: 380 nm – 1700 nm
- Viewing direction: 0°
- Aperture angle: 80°
- Tmax: 150°C
- Cooling medium: Air
- Option: Thermocouple

Spray pattern of direct injection
Borescope with diameter of 6.5 mm and standard length of 300 mm
Borescope tip: optics with air cooling outlet in axial direction
Illumination probes

In some cases, the injection spray is to be recorded as well as the intrinsic radiation from combustion; these situations require illumination probes to which a high-power light source is also connected. Size and positioning are critical factors in image quality. The scattered light method is in widespread use to capture images of the injection spray. This method involves illumination and image capture from the same direction. Illumination probes are available with a connection for air cooling as an option. It is not absolutely essential to equip illumination probes with air cooling, because they have greater resistance to high temperatures. However, air cooling is advisable if the probe is located at a distance from the cooling water channels in the cylinder head.

| Illumination probe with central air cooling |

**Dimensions and characteristics:**

<table>
<thead>
<tr>
<th>Diameter</th>
<th>4.0 mm, 6.5 mm, 8.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length:</td>
<td>variable (300 mm standard)</td>
</tr>
<tr>
<td>Aperture angle:</td>
<td>90°</td>
</tr>
<tr>
<td>Tmax:</td>
<td>250°C</td>
</tr>
<tr>
<td>Option:</td>
<td>Air cooling</td>
</tr>
<tr>
<td>Option:</td>
<td>Thermocouple</td>
</tr>
</tbody>
</table>

When dimensioning the optical accesses to the combustion chamber for the borescope and the illumination, the largest possible option should be chosen. Larger optical diameters result in images of better quality from the engine. If an illumination probe with an inner diameter of 8.0 mm and an 8.0 mm borescope are used, high-speed images can be captured with an exposure time of 1 µs.

Different versions are used depending on the optical diameter of the illumination probes. So that adequate light can be supplied for illumination, the light is fed through one, two or four coupling inlets. For larger cylinder diameters in particular, two or four coupling inlets are required. The standard versions are designed for the LED-P40, LED-P80 and LED-P160 illumination units from Kistler (data sheet LED-P40_003-414e).

<table>
<thead>
<tr>
<th>Illumination probe Outer diameter</th>
<th>Recommended number of light coupling inlets</th>
<th>Light source</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 mm</td>
<td>2</td>
<td>LED-P80</td>
</tr>
<tr>
<td>6.5 mm</td>
<td>2</td>
<td>LED-P80</td>
</tr>
<tr>
<td>8.0 mm</td>
<td>4</td>
<td>LED-P160</td>
</tr>
</tbody>
</table>

Illumination probe with central air cooling

Illumination probe with 4 light coupling inlets

Illumination probe with LED-P40 light source, without air cooling
Protective windows for optical probes
Protective windows onto the combustion chamber are essential to protect the sensitive borescopes and illumination probes. They protect the optics against the high pressures and temperatures that occur during combustion. The optical windows are positioned at the tip of a solid metal sleeve which is screwed into the cylinder head, flush with the combustion chamber. The material used for this purpose is sapphire, which ensures transmission across a wide range of wavelengths.

All-In-One probe
The range of optical probes from Kistler includes one outstanding innovation: the All-In-One probe (or AIO probe), which requires only one access to the combustion chamber for illumination and image acquisition. The light path is separate from the image path. This prevents reflections on the borescope’s protective window. Illumination is provided via a ring on the edge of the probe.

Dimensions and characteristics:
Inner diameter: 4.0 mm, 6.5 mm
Outer diameter: 8.5 mm, 11.5 mm
Length: 300 mm
Cooling medium: Air
Aperture angle of optical probe (illumination cone): 90°
Aperture angle of borescope (image area): 80°
Number of light coupling inlets: 1 or 2
Tmax: 300°C
Pmax: 150 bar

Dimensions of borescopes and optical probes

<table>
<thead>
<tr>
<th>Borescope Outer diameter</th>
<th>Optical probe Outer diameter</th>
<th>AIO probe Outer diameter</th>
<th>Number of light coupling inlets</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 mm</td>
<td>6.5 mm</td>
<td>8.5 mm</td>
<td>1 – 2</td>
</tr>
<tr>
<td>6.5 mm</td>
<td>9.0 mm</td>
<td>11.5 mm</td>
<td>2</td>
</tr>
<tr>
<td>8.0 mm</td>
<td>10.5 mm</td>
<td>---</td>
<td>4</td>
</tr>
</tbody>
</table>
Comparison of systems – selection criteria
The right choice of optical components is critical for image quality in minimally invasive measurement technology. Based on the use of an All-In-One probe with a 4.0 mm borescope, the results can be improved even further by using larger optics.

<table>
<thead>
<tr>
<th>AIO probe Inner diameter</th>
<th>Number of light coupling inlets</th>
<th>Image quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 mm</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>4.0 mm</td>
<td>2</td>
<td>130%</td>
</tr>
<tr>
<td>6.5 mm</td>
<td>2</td>
<td>300%</td>
</tr>
</tbody>
</table>

Image quality with different AIO probes

If a second optical access to the engine combustion chamber is feasible, further increases in image quality become possible. This configuration should be considered even though it is more technically challenging. However, increasingly compact combustion chambers with restricted possibilities for access mean that this option is not always possible. Compared to the All-In-One application, more light can be introduced into the combustion chamber through the second access for the illumination probe. Based on a yield of 100% with the AIO probe and a 4.0 mm borescope, it is possible to achieve substantial increases that result in even better image quality.

<table>
<thead>
<tr>
<th>Borescope Outer diameter</th>
<th>Outer diameter of illumination probe / number of light coupling inlets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.0 mm/1 4.0 mm/2 6.5 mm/2 8.0 mm/4</td>
</tr>
<tr>
<td>4.0 mm</td>
<td>125% 160% 320% 640%</td>
</tr>
<tr>
<td>6.5 mm</td>
<td>160% 200% 390% 780%</td>
</tr>
<tr>
<td>8.0 mm</td>
<td>215% 280% 560% 1120%</td>
</tr>
</tbody>
</table>

Image quality (100% = AIO probe with 4.0 mm borescope)

Improvement of the image quality of different borescopes depending on the number of light coupling inlets

Measurement setup for AIO probe

Measurement setup for single probes
Special borescopes and optical probes
The scope for using minimally invasive optical measurement techniques has expanded enormously in recent years. This has created new challenges, making it necessary to adapt optical components simultaneously with camera technologies. To take one example: probes and borescopes are now available for many different wavelength ranges. The functionality of the optics has also become highly diversified over time.

UV borescopes
Most optical investigations of combustion engines are carried out in the visible wavelength spectrum (380 nm – 780 nm). However, some processes involve radiation that is not visible to the human eye. One example of this is the flame front in spark-ignition engines: in this case, radiation is mainly emitted in the UV range around 307 nm.

Industrial optics of the type installed in borescopes are unable to capture this radiation. Kistler’s portfolio also includes special borescopes for this application area. The optics installed in them are made of special materials (quartz) that ensure transmission in the UV range. These UV borescopes (as they are known) are available in both rigid and flexible versions.

Flexible UV borescope with air cooling and thermocouple

Application areas:
- Flame propagation in spark-ignition engines
- Determination of knock location
- Spectroscopy

Dimensions and characteristics:
- Diameter: 4.0 mm (flexible or rigid), 6.5 mm (rigid)
- Length: 300 mm
- Transmission wavelength range: 190 nm – 1100 nm
- Viewing direction: 0°
- Aperture angle: 80°
- Tmax: 150°C
- Cooling medium: Air
- Option: Thermocouple

NIR borescopes
In the field of endoscopy, interest focuses not only on UV wavelengths but also on those wavelengths above the visible range: this is known as the near-infrared (or NIR) region of the spectrum. One example of an application area is the use of special cameras to determine the temperature of combustion chamber components. Kistler’s portfolio also includes NIR borescopes to ensure good light transmission in this wavelength range.

Air-cooled 6.5 mm NIR borescope (optimized for 900 nm – 1700 nm)

Application areas:
Determining the temperature of combustion chamber components, and investigations of catalytic converters

Dimensions and characteristics:
- Diameter: 4.0 mm, 6.5 mm, 8.0 mm
- Length: 300 mm
- Transmission wavelength range: 380 nm – 1700 nm
- Viewing direction: 0°
- Aperture angle: 80°
- Tmax: 150°C
- Cooling medium: Air
- Option: Thermocouple

Special versions
It is not always possible to use a standard borescope to capture images of all the relevant areas in the combustion chamber. For this reason, Kistler offers special versions that also make it possible to observe inaccessible areas. The tips of these borescopes and optical probes are angled to allow the required viewing direction.

Borescope and optical probe with optics angled at 30°
Borescope and optical probe with optics angled at 70°

**Application areas:**
- Injection spray investigations
- Intake manifold investigations

**Dimensions and characteristics of borescopes:**
- Diameter: 4.0 mm and 6.5 mm
- Length: 300 mm
- Transmission wavelength range: 380 nm – 1700 nm
- Viewing direction: 30°, 45° and 70°
- Aperture angle: 70°
- Tmax: 150°C
- Cooling medium: Air

**Dimensions and characteristics of optical probes:**
- Diameter: 8.5 mm and 10.5 mm
- Length: variable (293 mm standard)
- Outer geometry: customized, depending on the engine
- Tmax: 350°C
- Pmax: 250 bar