In-cylinder imaging diagnostics with highly efficient UV-transparent endoscopes

C. Gessenhardt[1*], R. Reichle[2], C. Pruss[2], W. Osten[2], C. Schulz[1]
[1]IVG, University Duisburg-Essen, Germany
[2]ITO, University Stuttgart, Germany

Laser-based in-cylinder diagnostics are well established in engine research. The requirement of large-scale optical accesses, however, makes the application expensive and time consuming. It furthermore limits the engine operation range to low loads and speeds. We introduce laser excitation and imaging optics with a minimal outer diameter of 10 mm (imaging optic) respectively 9 mm (excitation optics). The imaging optics allows the observation of a 30×30 mm^2 field with a working distance of 35–42 mm and provides a light intensity, which is higher than standard large-scale UV optics at the same image magnification. The particular features of the endoscopes are demonstrated in experiments at a fired IC engine, for example OH chemiluminescence and UV-LIF measurements.

Introduction

Laser-based diagnostics have been successfully used for the observation of fuel/air mixing and combustion process in IC engines [1, 2]. Especially imaging diagnostics are of interest where in combination with pulsed UV-laser light-sheet illumination laser-induced fluorescence (LIF) is used to observe the spatial distribution of fuel vapor, intermediate species or exhaust gas components.

Imaging measurements, however, are typically restricted to optical engines where a significant part of the cylinder liner and the piston surface are replaced by large-scale quartz or sapphire windows [3]. In these facilities, standard UV-transparent photographic lenses can be used for signal detection and conventional laser optics are used for light-sheet formation. The construction of optical engines, however, is expensive and time consuming. Furthermore, the engines can typically be used in a restricted speed and load range only. Finally, IC engines are very sensitive to modifications in the geometry and the thermal management, which is difficult to avoid when inserting large windows. Therefore, an interest in micro-invasive concepts that use endoscopic approaches has developed over the recent years. The aim is to enable in-cylinder laser-based imaging diagnostics at full-load and full-speed conditions in production-line engines without significant modification.

In the past, UV LIF has been used for imaging applications with standard endoscopes with limited success only because of weak signal intensities in the UV combined with poor lens speed of refractive UV endoscopes that are not specifically designed for engine applications [4].

In this paper we present new hybrid endoscopic light sheet forming and wide angle imaging optics for engine diagnostics. The design concept includes diffractive and refractive optics and enables measurements at multiple spectral bands with the same front endoscope. This is required for the application of two-detection-band techniques such as simultaneous visualization of chemiluminescence and soot or fuel spray. This paper describes the optical design and the application of the miniaturized hybrid imaging endoscope in combination with a light-sheet forming optic creating a homogeneous light sheet for imaging measurements in fired IC engines.

Optical Design

Hybrid imaging endoscope: The design requirements for the imaging endoscope to enable the application in passenger car IC engines were: Maximum entry diameter 10 mm, avoid stiff connections between camera and engine, provide high lens speed in the UV with multi-wavelength capability (different spectral bands of at least 60 nm each), allow imaging of a 30×30 mm^2 field at a working distance of 35–42 mm with a resolution better than 100×100 pixels, provide imaging on a 25 mm diameter image intensifier in at least 200 mm distance. The optical concept as shown in Figure 1 was laid out as a multi-stage system.

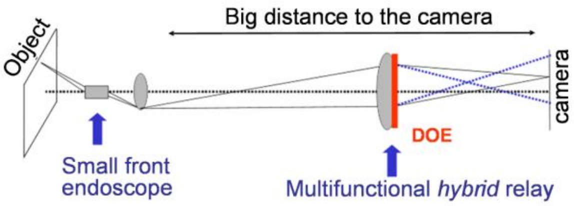

Figure 1: Optical design of the hybrid endoscope. Left: Front endoscope, right: Hybrid relay optics

The front endoscope is fixed in the cylinder head. It consists of two fused silica lenses and an additional field lens that deflects an uncorrected intermediate image towards the multifunctional relay. This element is fixed to the camera at a safe distance (20 cm) from the engine.

The chromatic correction is achieved by combining the positive dispersion of refractive optics with the strong negative dispersion of a diffractive element in the hybrid relay. The optimized aspheric phase function of the DOE corrects for further aberrations of the system.

* Corresponding Author: christopher.gessenhardt@uni-due.de

Two different hybrid relay elements have been developed. The first system is optimized in the spectral range from 275–350 nm (e.g. OH*-chemiluminescence or toluene LIF). A second hybrid relay was designed for detection in the 380−440 nm band. Both can be used simultaneously with the same front endoscope. Figure 2 (top) shows two parts of the endoscopic imaging system [5, 6].

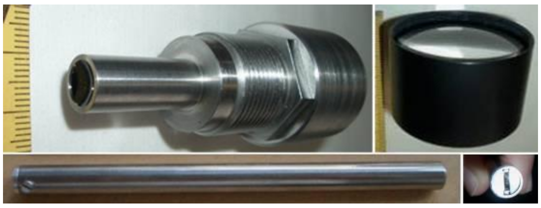

Figure 2: Endoscopic imaging system with front endoscope and relay element (top) and light sheet endoscope (bottom)

Light sheet forming optics: A micro-optical beam-shaping endoscope was developed with an outer diameter of 9 mm (Figure 2, bottom) [5]. It converts an incoming UV-laser beam into a divergent homogeneous excitation light sheet with a divergence angle of 22° and a width of <0.5 mm. The steel housing mounts cylindrical lenses inside a square, spark-eroded carrier channel.

Figure 3 shows the design of the beam-shaping endoscope with its beam pattern. The light-sheet endoscope uses three refractive cylindrical lenses (2-4). Lens 1 has an optimized aspheric shape for the conversion of the incoming Gaussian laser beam into a near-top-hat profile. For an excitation laser beam with a smooth Gaussian profile without hot spots the damage threshold of the excitation optics can be as high as 25 mJ.

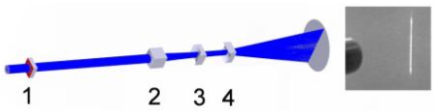

Figure 3: Design of the micro light sheet optics

Measurement Results

Demonstration of the performance of the miniaturized optics: In an atmospheric-pressure lab experiment (Figure 4) LIF measurements at a toluene-doped nitrogen flow have been carried out to contrast the hybrid endoscope with a commercial UV lens. A frequency-quadrupled beam of a Nd:YAG laser and the micro light sheet optic are used for excitation.

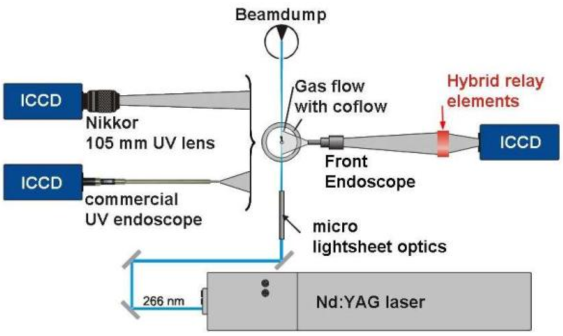

Figure 4: Experimental setup for demonstration measurements under lab conditions

With an arrangement leading to a similar paraxial object magnification at 313 nm (Hg line) the hybrid endoscope collects about 1.3 times more light than the standard UV lens (f = 105 mm, $f_{\#}$ = 4.5, *Nikon* / Figure 5).

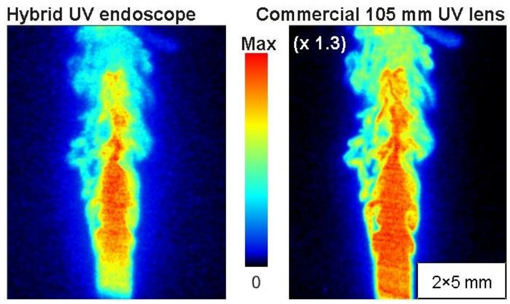

Figure 5: Comparison of the hybrid endoscope and a commercial UV lens by simultaneous LIF measurements of a toluene doped nitrogen flow

Engine application: To demonstrate the capabilities of the micro light sheet optics and the hybrid endoscope several demonstration measurements have been carried out at a SI production engine (BMW type: N46 B20). The schematic view of the setup for completely endoscopic light-sheet measurements is shown in Figure 6.

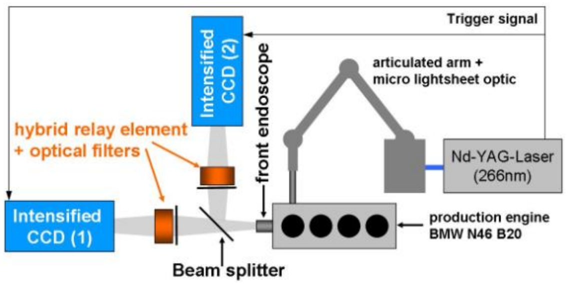

Figure 6: Measurement setup for detection of two spectral regions and laser illumination

The main engine modifications are two additional ports in the combustion chamber of the fourth cylinder for mounting the micro light sheet optics and the hybrid endoscope. A frequency-quadrupled Nd:YAG laser, an articulated arm and the micro light sheet optics are used for illumination.

The front endoscope is mounted in the cylinder head. The other imaging components have a distance of at least 20 cm to the cylinder head. The space in between the optical elements can be used for mounting optical filters or beam splitters. This allows to direct different wavelength bands to separate relays and cameras.

This two wavelength capability has been used for temperature measurements based on toluene LIF [7]. A technique, called two-color toluene thermometry, takes advantage of the red-shift of the toluene fluorescence spectra with increasing temperature [8]. By detecting two spectral regions of the toluene LIF signal simultaneously, local variations in temperature could be determined.

Chemiluminescence: The high lens speed of the endoscope in the UV allows for single-shot OH* measurements that can be used for the detection of cycle-to-cycle variations in flame propagation. Figure 7 shows a selection of single-shot images at 20°ca before TDC (ignition at 49°ca before TDC).

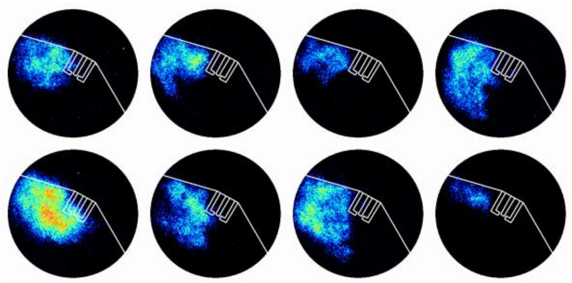

Figure 7: Single-shot OH chemiluminescence images (detection 312±17.5 nm)*

The wall of the combustion chamber and the spark plug are highlighted. During these measurements the engine was operated at low load (p_{mi} = 1.3 bar / n = 2040 min^{-1}) to show the applicability of the hybrid endoscopes with weak UV chemiluminescence signal.

Conclusions

This paper presents novel endoscopes for in-cylinder laser-light-sheet imaging with less than 10 mm entry diameter of the optics. An imaging endoscope combining diffractive and refractive optics provides imaging from a 30×30 mm^2 area at 35–42 mm working distance. The chromatic correction is provided by specifically designed diffractive elements. Both principal parts of the imaging system are separated, thus, engine and camera are not mechanically connected and engine vibrations do not affect the camera set-up.

In a laboratory setup it could be shown that the hybrid element provides 1.3 times stronger light signal compared to a standard $f_{\#}$ = 4.5 UV lens at the same image magnification. The usability of the hybrid endoscopes for multi spectral UV diagnostics has been proved in toluene LIF and OH*-chemiluminescence measurements at a production engine.

The combination of beam forming and imaging endoscopes significantly enhances the possibilities for laser-based in-cylinder imaging. It enables measurements in slightly modified engines under high load and speed conditions.

Acknowledgement

Funding by the German Federal Ministry of Education and Research (BMBF) is gratefully acknowledged.

References

1. Wolfrum, J., T. Dreier, V. Ebert, and C. Schulz, *Laser-based combustion diagnostics*, in *Encyclopedia of Analytical Chemistry*, R.A. Meyers, Editor. 2000, J. Wiley & Sons Ltd.: Chichester. p. 2118-2148.
2. Drake, M.C. and D.C. Haworth, *Advanced gasoline engine development using optical diagnostics and numerical modeling.* Proc. Combust. Inst., 2007. **31**: p. 99-124.
3. Espey, C. and J.E. Dec, *Diesel Engine Combustion Studies in a Newly Designed Optical Access Engine Using High-Speed Visualization and 2-D Laser Imaging.* SAE techn. Paper Series 930971, 1993.
4. Richter, M., B. Axelsson, and M. Aldén, *Engine diagnostics using laser-induced fluorescence signals collected through an endoscopic detection system.* SAE Techn. Paper Series 982465, 1998.
5. Reichle, R., C. Pruss, W. Osten, H. Tiziani, F. Zimmermann, and C. Schulz. *Hybrid excitation and imaging optics for minimal invasive multiple-band UV-LIF-measurements in engines*. in *VDI-Berichte 1959*. 2006: VDI-Verlag GmbH, Düsseldorf, Germany.
6. Reichle, R., C. Pruss, W. Osten, H.J. Tiziani, F. Zimmermann, and C. Schulz. *UV-Endoskop mit diffraktiver Aberrationskorrektur für die Motorenentwicklung*. in *Proc. DGaO 2006, www.dgao.de, Germany*. 2006.
7. Gessenhardt, C., F. Zimmermann, R. Reichle, C. Pruss, W. Osten, and C. Schulz, *Hybrid endoscopes for laser-based imaging diagnostics in IC engines.* SAE technical paper, 2009.
8. Koban, W., J.D. Koch, R.K. Hanson, and C. Schulz, *Absorption and fluorescence of toluene vapor at elevated temperatures.* Phys. Chem. Chem. Phys., 2004. **6**: p. 2940-2945.