

Thermodynamic and Optical Investigations on Particle Emissions in a DISI Engine at Boosted Operation

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ABSTRACT

The subject of this paper is the reduction of the particle number emissions of a gasoline DI engine at high engine load (1.4 MPa IMEP). To reduce the particle number emissions, several parameters are investigated: the large scale charge motion (baseline configuration, tumble and swirl) can be varied at the single cylinder engine by using inlays in the intake port. The amount of residual gas can be influenced by the exhaust backpressure. By using a throttle valve, the exhaust backpressure can be set equal to the intake pressure and hence simulate a turbocharger's turbine in the exhaust system or the throttle valve can be wide open and thus simulate an engine using a supercharger.

Additionally, higher fuel injection pressure can help to enhance mixture formation and thus decrease particulate formation. Therefore, a solenoid injector with a maximum pressure of 30 MPa is used in this work. The fuel composition also has a strong influence on the combustion process and on particulate formation. In this work, alkylate fuel is used to reduce the particulate number emissions at high engine loads.

In-cylinder spectroscopic measurements and high-speed visualization techniques are applied in the combustion chamber of the engine and the results are combined with measurement data taken with an FTIR in the exhaust of the engine. A conventional exhaust gas analyzer is also employed and cylinder pressure indication supports thermodynamic analysis. This one-dimensional, three pressure analysis (TPA) is performed using GT-Power.

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INTRODUCTION

The current trend towards engine downsizing and the focus on fuel economy and performance in combination with regulatory requirements with respect to combustion emissions require the development of new engine technologies. The introduction of the limit for particle number emissions (PN) in Europe with the legislative EU6c is a challenge for the development of gasoline DI engines [1; 2].

New combustion processes like stratified charge operation [3; 4] and new valvetrain variabilities [5] focus mainly on the optimization of the low load range of DISI engines. Another approach to reduce the fuel consumption and exhaust gas emissions is the hybridization. Thereby the vehicle can be driven by an electrical machine and the additional combustion engine is only needed for high power output during accelerations and to increase the range of the vehicle [6]. Thus the combustion engine is more often operated at higher engine load.

Even though the highest emission of PN is during the cold start phase of the engines and during catalyst heating [7], the acceleration process and the higher engine load become more and more relevant to meet the emission limits. With respect to new driving cycles like

the worldwide harmonized light duty vehicle test cycle (WLTC) and real driving emissions (RDE), which will be introduced with EU6c [8], the region of higher engine load is becoming an important development objective. Especially at low engine speed the mixture preparation is problematic because of the low flow velocities in combination with the high amount of injected fuel [9]. Thus the engine operation point for the investigations in this paper is chosen at 2000 rpm and 1.4 MPa indicated mean effective pressure. Large scale charge motion like tumble and swirl can improve the mixture preparation. Therefore, three different charge motion strategies were investigated: The baseline configuration of the naturally aspirated engine with low bulk charge motion, a tumble flow configuration, and a swirl flow configuration.

Another possibility to reduce the emission of PN is to increase the fuel injection pressure. Schumann et al. state that an increase of the injection pressure up to 80 MPa can not only reduce the PN emission but also the emission of nitrogen oxides and hydrocarbons during catalyst heating [10]. In Schumann's work, the injectors as well as the high pressure pump were diesel components. Befrui et al. show the potential of injection pressures up to 40 MPa at 2500 rpm and medium load (0.69 MPa) to reduce the PN emission [11]. The authors also

show the influence of different nozzle configurations (high and low static flow; number of holes) on the exhaust gas emissions and engine performance. In this work, an injector capable of injection pressures up to 30 MPa is used to investigate the impact of injection pressure on the mixture formation process at high engine load in combination with the different charge motion strategies described above.

The fuel composition has a big impact on the combustion and emission behaviour of a combustion engine. Thewes et al. studied the influence of different fuels on the emission and combustion behaviour of a single cylinder engine with centrally mounted injector [12]. Tetrahydro-2-methylfuran is tested in comparison to 1-Butanol and 2-Butanol while Ethanol, Isooctane and conventional RON 95 fuel serve as the state of the art bio- and non-bio-fuels to assess the findings with the other fuels. The authors observe that engine operation with butanol in general leads to increased hydrocarbon and PN emissions while ethanol just causes increased hydrocarbon emissions. This behaviour is assumed to be caused by improper mixture preparation, which could be affirmed by oil dilution measurements. These results fit to the work of Jin et al. who measure a rise of propene, 1,3-butadiene and acetylene emissions, which cause benzene formation [13]. Aromatic compounds like benzene are a known precursor for soot and particle formation [14].

Because of the negative impacts of alcohol-containing fuels on hydrocarbon and PN emissions shown by Thewes and Jin, Dageförde et al. compared RON 95 with ethanol and butanol blends (40 % alcohol, 60 % RON 95) on a single cylinder research engine with centrally mounted injector during catalyst heating operation [15]. The authors also use Toluene as neat aromatic compound and two alkylate fuels. The aromatic compounds support the particle formation process as already mentioned. Alkylate fuel is a mixture of different hydrocarbons comparable to RON 95 but with an aromatic compound close to 0 %. The composition of alkylate fuel is compared to the composition of RON 95 in Figure 1. The reduced amount of aromatics is substituted by a higher amount of iso-paraffins. Results of Dageförde et al. show that the amount of hydrocarbon and PN emissions are the highest for Toluene and can be reduced by using alkylate fuel with the lowest amount of aromatic compounds. The influence of alcohol-containing fuel is thereby dependent on multiple interacting effects like the caloric value, surface tension, viscosity, evaporation heat etc. For the investigations in this paper only RON 95 and alkylate fuel are chosen to show the influence of the lower aromatic compound, but with comparable fuel properties.

Aikawa et al. [16] discuss the attempt to predict particle emissions of gasoline engines by the composition of the fuel. They developed a model for PFI engines that correlates the particle number emissions with the vapour pressure and the double bond equivalent of the components of the fuel. Leach et al. [17] tried to transfer the model to DISI engines. Both investigations show a direct correlation of the vapour pressure and the double bond equivalent to the PN emissions.

Results shown by Berndorfer et al. [18] state that deposits at the tip of the injector cause a diffusion flame at the injector tip late in the combustion cycle. A correlation between optical investigations of these diffusive flames show a correlation to measured PN emissions. Even though the spray characteristics such as the spray cone angle,

penetration and droplet size spectra are not impacted, the PN emissions rise. The authors state that the diffusion flame close to the injector tip is a strong contributor to both PM and PN emissions at steady state warmed-up engine conditions and that most of the injector caused PN drift occurred during the build-up of the deposits. Thus the injector is cleaned during these investigations before each variation to eliminate the influence of these deposits.

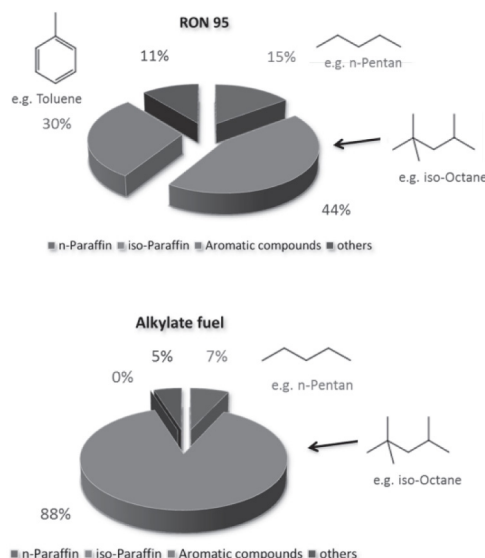


Figure 1. Fuel Composition of RON 95 and alkylate fuel [19]

A particle concentration measurement taken in the exhaust is not enough to understand the particle formation in the combustion chamber of spark ignition engines. The soot formation in Diesel engines is easier to measure because of the local soot formation in the area of the fuel injection and the high amount of soot because of the mixture inhomogeneity. Thus even complex measurement systems like RAYLIX® can be used and can help to understand the formation and oxidation processes of the soot [20; 21].

With the implementation of direct injection in gasoline engines and the related shorter time for the mixture preparation, a deeper understanding of the soot formation in gasoline engines is also needed. Because of the lower amount of soot, the established measurement techniques of the Diesel investigations cannot be used directly and some effort has to be taken to increase the knowledge about particle formation and oxidation in gasoline engines.

A fiber-optical sparkplug in combination with two particle measurement devices is used by Sabathil et al. [22]. A four-cylinder engine with a centrally mounted multi-hole injector is operated in transient and stationary operation. Several parameters such as the air-fuel-ratio (A/F ratio), injection timing, injection pressure as well as the coolant temperature are varied to get a better understanding of the particle formation process in a GDI engine. The authors state that the A/F ratio as well as the injection timing and the combustion phasing have the strongest influence on the particle formation. The fuel pressure and the coolant temperature have a medium influence and the external EGR ratio only a small influence on the PN emission.

Cudeiro Torruella et al. investigate the soot formation in a spray guided DISI four cylinder engine with lean stratified operation [23]. The two-colour method as well as high-speed-visualization is used to understand the in-cylinder soot formation. A laser induced incandescence system is used in the exhaust gas and the results are compared to a condensation particle counter. The authors show that a correlation between the soot luminescence inside the combustion chamber and the measurement in the exhaust gas is not possible under all conditions. The authors state that individual cycles with high emission of PN cause a high particle concentration in the exhaust gas. Therefore the measurement of the particle concentration alone is not enough to understand the particle formation in gasoline engines.

Because gasoline fuel consists of a high number of different components, the combustion of these fuels is complex and a high number of substances are created during combustion. These different substances emit light at different wavelengths. In Figure 2 the radiation of some substances by a hydrocarbon flame is shown. It is obvious that most of the species emit radiation at different wavelengths. Substances like H_2O and CO_2 emit radiation at several wavelengths. However, soot can be considered as a band radiator and emits light at higher wavelength in the red and infrared area [24]. The broadband radiation from soot is strongly dependent on temperature and the spectral intensity changes with temperature. Techniques that rely on visible soot radiation may not show all of the soot, especially at cold temperatures.

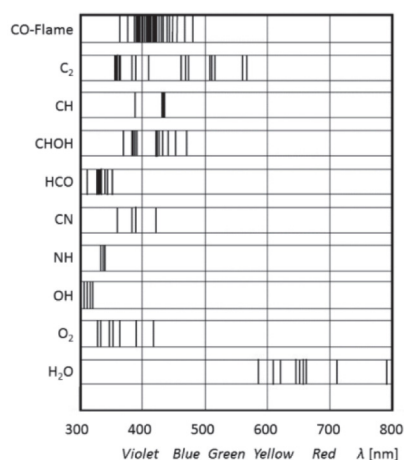


Figure 2. Essential radiation spectra of a hydrocarbon flame [24]

A spectrograph is used besides a high-speed-imaging system in these investigations to get more information about the composition of the emitted light.

Storch et al. investigate soot formation of ethanol blends in a single cylinder engine using high-speed-visualization in two operation points [25]: catalyst heating and homogenous with rich A/F ratio. By using a stereoscope and different filters for OH^+ chemiluminescence (308 nm) and soot luminescence (568 nm) a simultaneous separation of the combustion process and the soot formation is possible. The authors state that this separate measurement of the emitted light is needed to distinguish between different causes of the emitted particles.

EXPERIMENTAL SETUP

Test Bench Setup

The test bench at the Institute of combustion engines (IFKM) is equipped with several measurement devices: The fuel consumption is measured via a Pierburg PLU 401. The exhaust A/F ratio is measured using an ETAS LA4 Lambda Meter. For exhaust gas emissions a Pierburg AMA2000 (THC, NO_x , CO , CO_2 , O_2) is used. Additionally an FTIR (MKS MultiGas 2030, specifications in [26]) with a high pressure sampling module by IAG is used for the differentiated analysis of the composition of the exhaust gas. The general setup of the test bench is shown in Figure 3.

Besides the gaseous exhaust emissions the particle number emissions are measured: A chamfered sample probe is mounted and connected to an AVL 489 Particle Counter Advanced [27]. The short (0.5 m) sample line between probe and primary dilution (Chopper diluter) is heated to 190 °C. The following evaporation tube and second dilution stage are connected to the chopper diluter via a heated line. These three devices combined form the “Volatile Particle Remover” (VPR) that operates according to the guidelines of the “Particle Measurement Programme” (PMP) [28]. The overall dilution can be adjusted between 100:1 and 2000:1 depending on the particulate number concentration in the exhaust gas. Downstream the VPR the conditioned sample gas is split. A part of the gas stream is fed to the TSI 3790 “Condensation Particle Counter” (CPC) of the AVL device. The rest of the diluted gas is fed to a TSI 3090 “Engine Exhaust Particle Sizer” (EEPS) [29]. The CPC fulfils the requirements of the UNECE-R83 with a counting efficiency of 50 % for particles with 23 nm (± 1 nm) electrical mobility diameter. The maximum measureable particle diameter is 2.5 μm . The EEPS is not conforming to UNECE-R83 but it is attached to complement the measured particulate number concentration of the AVL device with information about particle size distribution between 5.6 nm and 560 nm electrical mobility diameter.

The in-cylinder pressure is measured using a Kistler 6054AR piezo-electric pressure transducer. In combination with the low-pressure piezo-resistive transducers (Kistler 4045 and 4075) mounted in intake and exhaust runners, the pressure signals are the basis for a GT-Power TPA model of the engine. To validate the TPA, the engine is equipped with a temperature sensor in the combustion chamber. The thermal probe is a thermocouple (NiCr-Ni) with an open ending (contact of the wires is in the combustion chamber). This method is also used by Hgel et al. for measurements of the wall heat flux on a single cylinder gasoline engine [30]. With this method a mixture of gas- and wall-temperature is measured. The average temperature measured by the sensor is used for the wall temperatures in the TPA. With the TPA the internal EGR, the rate of heat release (ROHR) and other relevant thermodynamic quantities can be calculated. The pressure signals are acquired with a resolution of 3,600 pulses per revolution.

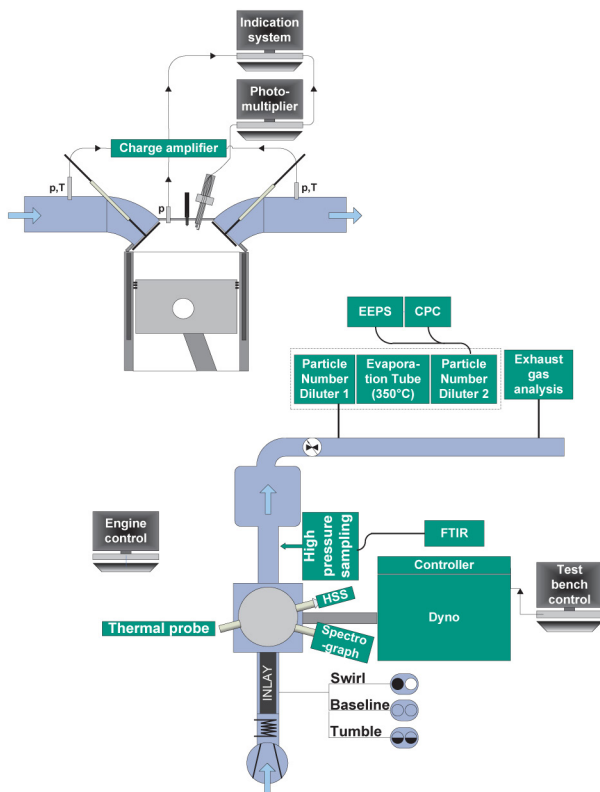


Figure 3. Test bench setup

Engine Data

The engine used for the investigations is a single cylinder research engine. Technical data of the engine is shown in Table 1.

Table 1. Engine data

Displacement (V_d)	[cm ³]	498
Stroke	[mm]	90
Bore	[mm]	84
Compression ratio	[-]	10.5:1
Intake valve spread	[°CA aTDC _g]	60 – 120
Exhaust valve spread	[°CA bTDC _g]	60 – 120
Valve lift (intake/exhaust)	[mm]	9.7 / 9.7
Rail pressure	[MPa]	max. 30
Injection system	[-]	central mounted DI

The engine is equipped with cam phasers both on intake and exhaust side and a centrally mounted injector. The spark plug and the injector are mounted in the longitudinal direction of the crankshaft.

For the investigations a constant engine speed of 2000 rpm is chosen with an IMEP of 1.4 MPa. The relative air-fuel ratio (λ) is set to 1. The point of 50 % mass fraction burned (MFB50%) is kept constant for all variations at 28 °CA aTDCf. At this operation point, the knock limited spark advance results in an MFB50% at 20 °CA aTDCf. Because the point of 50 % mass fraction burned has a strong influence on combustion duration and thermodynamic conditions

during combustion it is advantageous to keep the point of 50 % mass fraction burned constant for all variations instead of driving at the optimum for each point. The other constant operating parameters are listed in Table 2.

Table 2. Engine operating conditions

Engine speed	[rpm]	2000
IMEP	[MPa]	1.4
MFB50%	[°CA aTDCf]	28
Rel. A/F-ratio (λ)	[-]	1
T _{Oil}	[°C]	90
T _{coolant}	[°C]	90
T _{Charge air}	[°C]	30

Injector

The six hole solenoid actuated injector is a commercially available Delphi M14. The spray targeting is adapted for the single cylinder research engine. For these investigations the engine is only operated with a single injection in the intake stroke resulting in a homogenous operation. The technical data of the injector is shown in Table 3 and the spray targeting is visualized in Figure 4.

Table 3. Injector data

Injector type	[-]	Multi-hole injector
Q_{stat}	[g/min]*	820
Max. rail pressure	[MPa]	30
Spray type	[-]	six hole spray
Spray angle	[°]	75

*at 100 bar n-heptane

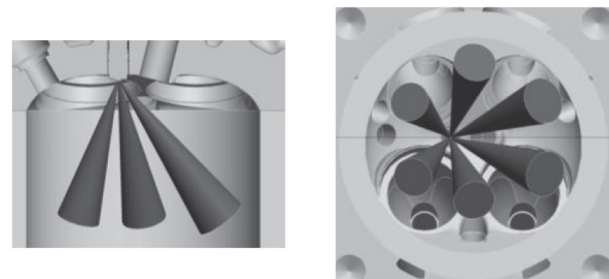


Figure 4. Spray targeting

Fuel Properties

The goal of this paper is to investigate the influence of RON 95 and alkylate fuel on the combustion behaviour and exhaust gas emissions. The basis for the comparison is commercially available RON 95 with 5 % ethanol. Alkylate fuel (Viking MotoPlus®) shows potential to reduce particulate formation by eliminating the fraction of aromatic compounds in the fuel composition. The aromatic compounds are mainly substituted by iso-paraffins, see Figure 1. This leads to different C, H and O mass fractions compared to RON 95. The research octane number is on the same level. Additional fuel parameters are shown in Table 4.

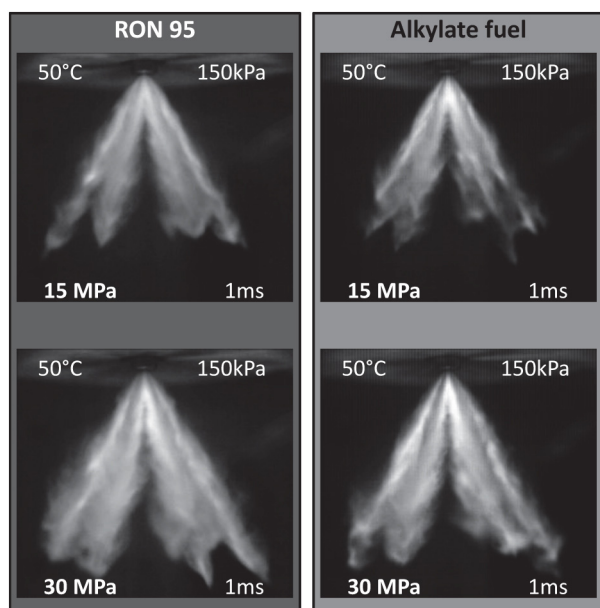


Figure 5. Spray visualization: RON 95 (pictures on the left hand side) and Alkylate fuel (pictures on the right hand side) at 15 MPa (upper row pictures) and 30 MPa (bottom row pictures) at 50 °C and 150 kPa

Table 4. Fuel properties

		RON 95 (E5)	Alkylate Fuel
Density **	[g/cm ³]	0.75	0.7
Caloric value	[MJ/kg]	42.35	44.55
RON	[-]	95	95
MON	[-]	85	>90
Sensitivity S	[-]	10	<5
Vapour pressure	[kPa]	50-65*	45-100*
Kin. Viscosity **	[10 ⁻⁶ mm ² /s]	0.53*	0.53*
Surface tension **	[mN/m]	20*	20*
Evaporation heat	[J/g]	350	210
Carbon mass fraction	[%]	84.25	84.19
Hydrogen mass fraction	[%]	13.51	15.81
Oxygen mass fraction	[%]	2.24	0
C/H-Ratio	[-]	6.24	5.33
Aromatic volume fraction	[%]	28.3	<0.1
Stoichiometric A/F	[-]	14.27	15.1

* based on published data (no test fuel specific data)

** at 20 °C

The spray characteristics such as the spray cone angle, penetration and droplet size spectra change depending on the injection pressure and the fuel characteristics. Thereby the higher injection pressure used in these investigations helps to create smaller droplets with higher impulse and thus deeper penetration. This behaviour is shown for the used injector in Figure 5 for 15 and 30 MPa injection pressure and both fuels. Each image of the Mie-scattering signal is measured using the high-speed-camera in a pressurized chamber at the same time step

(1 ms after SOI). The conditions in the pressure chamber are adjusted to meet the conditions in the single cylinder (150 kPa and 50 °C). The images show visible increase of light scattering by the spray plume with higher injection pressure for both fuels and a steeper spray penetration. According to Hoffmann et al. the higher scattered intensity is an indicator of the droplet-size reduction associated with the system pressure increase [31]. With the smaller droplet size the surface increases and more light is scattered. Comparing RON 95 to Alkylate fuel a slightly higher intensity associated with smaller droplet sizes is obvious for both injection pressures.

Fuel Properties and Engine Knocking

The anti-knock quality of a fuel depends on the fuel composition as well as operation conditions. This quality is traditionally described by the research and motor octane number which are measured at two different pressure / temperature conditions in a single cylinder engine. These values are shown for the two fuels used in Table 4. The sensitivity S of the fuel is defined as RON-MON. However the true anti-knock quality of a fuel is better described by the octane index OI.

$$OI = (1-K) RON + K \times MON = RON - K \times S.$$

K is a constant which depends on the pressure and temperature evolution in the unburned gas and is therefore not a primary property of the fuel. Recent studies by Kalghatgi [32; 33; 34], Amer et al. [35] as well as Mittal and Heywood [36] show that K can even be negative in modern SI engines. This is caused by the higher thermal efficiency of the engines. Therefore the pressure for a given temperature is higher in modern engines compared to the RON test. Results of Mittal and Heywood [37] show that the K value has decreased in the U.S. from around 1 in the 1930s to close to zero in 2008. These results indicate that a fuel with equal RON, lower MON and thus a higher sensitivity can be more resistant to knocking especially at boosted operation.

Experimental Setup

Valve Timings

For the investigations one valve timing combination is chosen. The operating point is characterized by a valve overlap close to 0 °CA. The exhaust valve opens at 120 °CA aTDCf and the intake valve opens at 325 °CA aTDCf. By choosing this valve timing combination scavenging effects can be excluded for the investigations.

Exhaust Backpressure

The single cylinder research engine is equipped with an externally driven compressor for supercharging. The exhaust backpressure can be set independently by adjusting a throttle in the exhaust system downstream of the exhaust surge tank, as shown in Figure 3. For the investigations two possible settings are used: The supercharger configuration simulates an engine driven by a supercharger with a dethrottled exhaust system. The second setup simulates a turbocharged engine where the exhaust backpressure is set equal to the charge air pressure. The symbolic images of the two combinations are shown in Figure 6.

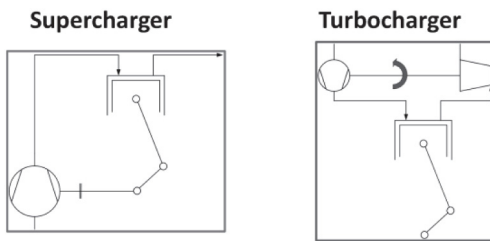


Figure 6. Configurations for the exhaust backpressure

Large Scale Charge Motion

The in-cylinder charge motion influences the mixture formation. With an optimized charge motion the emission of exhaust gas emissions as well as the emission of PN can be reduced.

The single cylinder research engine used is originally designed for natural aspiration. Therefore the intake channels are designed for minimum flow losses and maximum charge. This leads to a low in-cylinder charge motion. To assess the influence of an increased in-cylinder flow, two inlays in the intake channel are used to generate a tumble or a swirl motion. The inlays are shown in Figure 7. The tumble is realized with an inlay that covers 60 % of the lower part of the intake channels. The swirl inlay covers one of the valves completely.

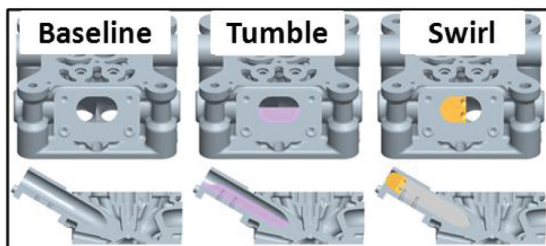


Figure 7. Inlays for large scale charge motion

Setup Optical Measurement Technique

The engine is equipped with endoscopic accesses to the combustion chamber, whereby an optical sleeve with a sapphire window can be mounted at each access. One of those was used for the high-speed-visualization, one for a thermal probe and one for the spectrograph. The layout of the cylinder head including the optical accesses is shown in Figure 8.

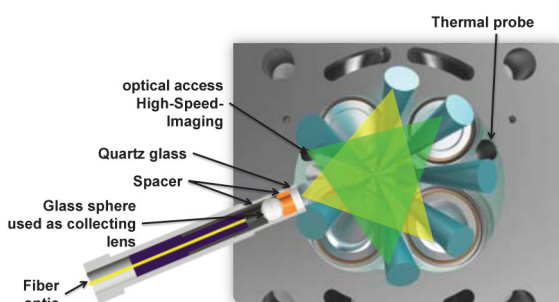


Figure 8. Setup of the optical accesses

High Speed Visualization

For the high speed visualization, a CMOS camera is used (LaVision HSS6) as shown by Disch et al. [38]. The camera is operated with the corresponding commercial software DaVis 7.2. It has a maximum resolution of 1024×1024 pixels ($20 \mu\text{m}$ per pixel). The repetition rate of 13.5 kHz the camera chip used is reduced to an area of interest of about 512×512 pixels. This lowers the memory required to store the images on the camera. The camera start-trigger is adjusted with a synchronizing system to position it to the required crank angle degrees. The camera start trigger and the sampling trigger are logged together with the cylinder pressure signal and the other measured parameters. For every operating point, 200 consecutive combustion cycles, each consisting of 180 images (observation over 160°CA), are recorded.

Additionally to the High-speed-camera a 12-bit CCD camera (LaVision Imager Compact) is used in combination with a flash lamp to visualize the injection. The optical access used for the HSS is used for the CCD camera and the optical access of the spectrograph is used for the illumination as shown in Figure 3. The maximum sampling frequency of the camera is 11 Hz at a resolution of 1390×1024 pixels.

Spectrograph

The second optical access on the power take off side is used for the spectrographic measurements. This setup is also used by Hampe et al. for measurements concerning a high-frequency ignition system [39] and by Beck et al. for measurements in a small two-stroke SI engine [40]. In the sleeve a ball lens to enlarge the field of vision and a UV-VIS optical fiber bundle is inserted. The optical signal is fed into the spectrograph (Princeton Instruments Acton SP2500). The functional principle of a spectrograph is shown in [41]. The chosen grating covers a wavelength range of 200 nm on the 580 pixels of the CCD camera, resulting in a spectral resolution of 0.34 nm per pixel. Accordingly three measurements are performed for each operation point to cover the wavelength range from 280 nm to 880 nm. The calibration of the spectrograph is checked with a mercury UV lamp [42]; the maximum and mean deviations are 0.45 nm and 0.3 nm, respectively. The spectral transmissivity of the optical fiber bundle is shown in [43]. The characteristic curve of the HQf photocathode used in the spectrograph has its maximum quantum efficiency at about 500 nm and drops to 50 % at 360 nm and 685 nm and is shown in Figure 9. The exposure time for each measurement is 200 μs which corresponds to 2.4°CA at 2000 rpm engine speed. 100 cycles are accumulated at each point to reduce the noise level. The measurements are done relative to the ignition timing. The recording times are ignition timing plus: 10, 15, 20, 25, 30, 40, 50 and 60 $^\circ\text{CA}$. The measurement with the High-Speed-Camera is simultaneous to the first spectrographic measurement at 10 $^\circ\text{CA}$ after ignition timing.

The characteristic curves of the High-Speed-Camera and the spectrograph used are shown in Figure 9. It is obvious that the measured intensity for both systems is a function of the emitted wavelength. Therefore conclusions by the absolute intensities of the whole spectrums are difficult. But relative comparisons at same wavelengths are reliable if there are no deposits on the optical path.