

Effects of Mixture Stratification on Ignition and Combustion in a GCAI Engine

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ABSTRACT

Fuel consumption and NO_x emissions of gasoline engines at part load can be significantly reduced by Controlled Auto-Ignition combustion concepts. However, the range of Gasoline Controlled Auto-Ignition (GCAI) operation is still limited by lacking combustion stability at low load and by high pressure-rise rates toward higher loads. Previous investigations indicate that the auto-ignition process is particularly determined by the thermodynamic state of the charge and by stratification effects of residual gas, temperature, and air-fuel ratio. However, little experimental data exist on the direct influence of mixture stratification on local ignition and heat-release rate (HRR) in direct-injection (DI) GCAI engines, because it is challenging to measure all the relevant charge and combustion parameters quasi-simultaneously with sufficient spatial/temporal resolution and precision.

In the present article, a newly designed laser-diagnostic approach is therefore presented, in which one-dimensional Spontaneous Raman Scattering (SRS) is combined with high-speed chemiluminescence imaging. SRS yields the composition of the charge along a line in terms of air-fuel ratio, exhaust-gas content, and temperature. Thereby, the mixture formation process is analyzed. Additionally, high-speed chemiluminescence imaging is conducted in the same experiment, in order to characterize the ignition and combustion process with relatively high temporal and spatial resolution. In particular, the influence of the three charge parameters, which are measured shortly before combustion, on the ignition process is investigated by exploiting the combined results of both optical techniques.

The results show that first auto-ignition in each cycle is basically determined by the gas-phase temperature, which depends on both the residual-gas distribution and local vaporization cooling. Thus, large-scale thermal stratification of the charge leads to a staged combustion process, which progresses from high-temperature to low-temperature regions. However, the progress of combustion and the resulting maximum heat-release rate also depend on the small-scale inhomogeneity in the mixture, which can be controlled by the fuel-injection timing. Furthermore, it is demonstrated that the stability of combustion phasing is dependent on the cyclic variability in the gas-exchange process.

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INTRODUCTION

The Controlled Auto-Ignition of gasoline has the potential to significantly cut down CO₂ emissions by up to 30% and dramatically reduce NO_x emissions, in contrast to conventional throttled engine operation [1]. The reduction in fuel consumption is mainly driven by the dethrottling of the intake system, the low-temperature combustion, the optimized charge

properties, due to the lean mixture, and the comparatively quick combustion process. High amounts of trapped residuals from the previous combustion cycle initiate the auto-ignition, probably due to both thermal and chemical effects [2] and references therein. The distinct reduction in NO_x emissions, which is caused by the low-temperature combustion, provides the vision of reduced fuel consumption due to stratified lean combustion without the drawback of additional NO_x.

aftertreatment. Nevertheless, this combustion system has a limited operational range [3]. Toward low engine loads, the decreasing exhaust enthalpy leads - despite highest trapped residual rates - to a deteriorated combustion and finally to misfiring. Toward higher engine loads, the maximal pressure-rise rates and NO_x emissions increase significantly.

In general, Controlled Auto-Ignition can be influenced by:

- The global pressure and temperature level in the combustion chamber (e.g. determined by the trapped amount of residuals, the compression ratio or the thermodynamic conditions in the intake system),
- the local stratification of residuals, temperature as well as air/fuel ratio (depending on the calibrated injection strategy [2, 3, 4, 5] or the used exhaust-gas strategy, i.e., either Exhaust-Port Recirculation (EPR) or Combustion-Chamber Recirculation (CCR) [2, 3, 6, 7]),
- fuel properties as discussed in [8] and references therein.

Similarly, it was demonstrated in Homogeneous Charge Compression Ignition (HCCI) or Reactivity Controlled Compression Ignition (RCCI) engines, respectively, that the combustion pressure-rise rate could be smoothed by partial fuel stratification or by creating a range of ignitability in the charge, based on two fuels with different reactivity [9, 10, 11, 12] and references therein. Thereby, the high-end limits for HCCI/RCCI operation could be increased.

However, detailed experimental in-cylinder data on the direct local effect of mixture stratification on ignition and combustion in Gasoline Controlled Auto-Ignition (GCAI) engines are lacking. Thus, it is the primary objective of the present study to investigate this effect by advanced optical diagnostics, which yield the most important mixture-composition and combustion parameters quasi-simultaneously.

Interestingly, the effect of mixture formation on combustion was studied by combined optical diagnostics in a Controlled Auto-Ignition engine, which was operated with Port-Fuel Injection (PFI) [2]. Combustion was visualized by chemiluminescence imaging, and both air-fuel ratio and residual-gas content were measured by planar Laser-Induced Fluorescence (LIF) in different experiments, based on a fluorescent tracer, which was seeded into either the fuel or the intake air, respectively. The resulting conclusions are compared to the present observations in the Results and Discussion section. Tracer-based, planar LIF measurements were also conducted previously, in order to obtain the in-cylinder distributions of the fuel [2, 13, 14, 15, 16, 17, 18, 19], the residual gas [20], or the temperature [13, 20, 21, 22, 23], respectively, in other GCAI/HCCI gasoline engines. However, LIF generally depends on the in-cylinder pressure, temperature, and chemical charge composition [24]. Thus, quantification of the LIF signals is challenging in most real engine environments. For instance, tracer-based LIF conducted previously in a direct-injection spark-ignition (DI-SI) engine in the authors' lab [25] cannot readily be applied to GCAI engines, because of the high Exhaust Gas

Recirculation (EGR) rate of about 50%. Due to the resulting high effort of (quantitative) LIF studies, simultaneous spatially resolved measurements of fuel distribution, residual gas, and temperature of the charge by LIF have not been achieved by now. Essentially this also holds for planar phosphor thermometry [26], point-wise Coherent Anti-Stokes Raman Spectroscopy (CARS) [27], and line-of-sight infrared (IR) absorption spectroscopy [28]. It should also be noted that fuel-tracer-based diagnostics are often affected by preferential evaporation, due to different volatilities of fuel and tracer, respectively, in particular in DI gasoline engines [29, 30, 31].

In order to measure the three key parameters of the charge simultaneously, one-dimensional (1-d) Spontaneous Raman Scattering (SRS) is applied in the present study. Multi-species and temperature measurements by SRS were previously conducted in SI engines [32, 33]. Note that a fuel tracer is not required, but a transparent surrogate fuel has to be used. Iso-octane is chosen in the present study, because it is a widely used surrogate for gasoline, since it has similar auto-ignition and combustion characteristics [34]. Prior-cycle effects of energy conversion, which are also investigated in the present article, were previously studied by SRS in a conventional SI engine with PFI [35].

Combustion in GCAI/HCCI gasoline engines was also characterized previously by planar LIF in [16, 17, 36, 37, 38]. Both formaldehyde and OH radicals were probed. However, planar OH or H_2CO LIF generally yields only about one quasi-instantaneous image per engine cycle in the present state of the art. Thus, the temporal evolution of the ignition and combustion process can hardly be characterized by planar LIF in single cycles. Instead of using LIF, auto-ignition and combustion are therefore visualized by high-speed chemiluminescence imaging in the present experiment. Optical access to the combustion chamber is achieved relatively easily for this diagnostic, because a laser beam is not required. Chemiluminescence imaging was previously conducted in GCAI/HCCI gasoline engines in [2, 3, 4, 5, 9, 13, 14, 15, 38, 39, 40, 41, 42]. A particularly detailed spectroscopic analysis of the naturally occurring light emission in an HCCI engine was presented in [34].

EXPERIMENTAL

Single-Cylinder Research Engine Set-Up

For the engine investigations a naturally aspirated direct-injection single-cylinder research engine is used. Injector and spark plug are placed in central cross position in the combustion chamber roof with the spark plug installed between the intake valves (IV) and the injector being installed between intake and exhaust valves (EV). The engine is equipped with a fully variable electro-mechanical valve train, which provides high degrees of freedom regarding the desired valve timings. For the tests a piezo-actuated injector is used [43, 44]. Tab. 1 provides an overview of the technical data of the test engine. The combustion-chamber geometry is outlined in Fig. 1. The matching all-metal engine is described in [8].

The cylinder, intake, and exhaust gas pressures are sampled with at least 1 °CA resolution over 200 consecutive engine cycles for the calculation of all indicated values. Higher resolution is used around top dead center. Pressure transducers and thermocouples are used for static pressure and temperature measurements. Oil and water conditioning systems allow steady-state operation and are set to 90 °C. The intake air is conditioned to 50 °C upstream from the throttle flap. The pressures upstream from the throttle flap and in the exhaust manifold are controlled to 1013 mbar during motored operation.

Table 1. Technical data of the research engine.

Displaced volume	499 cm ³
Stroke	90 mm
Bore	84 mm
Number of valves	4
Valve lift	8 mm
Compression ratio	12:1
Fuel injector	outwards-opening hollow-cone piezo (Continental Company)
Fuel pressure	100 bar

For the present study the following abort criteria are chosen as boundary conditions for Controlled Auto-Ignition:

- A standard deviation of the net indicated mean effective pressure (IMEP) of > 0.15 bar,
- a maximum cylinder-pressure rise rate of > 5 bar/°CA, or
- a stoichiometric ratio (λ) < 1, i.e., fuel-rich conditions, according to the definition in the Data-Reduction subsection.

CCR is chosen as the strategy for Controlled Auto-Ignition operation [3]. It is characterized by comparatively short valve opening events and therefore a long negative valve overlap (NVO) period. The early closing of the exhaust valves enables high degrees of freedom in the calibration of different injection strategies.

Two selected operating conditions, denoted A and B, respectively, are basically discussed in the following sections. A single fuel-injection event per engine cycle either in the intake or the compression stroke is used for both conditions. Mixture stratification is strongly different for these two conditions, due to the chosen fuel-injection timing given in [Tab. 2](#). The valve timing and EGR rate are very similar for both conditions, as noted in [Tab. 2](#). Thus, auto-ignition phasing is also approximately equal, as shown below. All other operating conditions are equal. Spark assistance is not applied. Note also that the engine operation conditions are not optimized for ignition phasing, since it is the objective of this work to investigate the effects of mixture stratification. In order to start each experiment from a consistent baseline, after switching from SI to GCI operation always the same dwell time is applied before starting the data acquisition.

Table 2. Specifications of the selected operating conditions. All crank angles are given with regard to top dead center of combustion (TDC).

Operating condition	A	B
Speed	2000 rpm	2000 rpm
EGR (by mass)	49 %	51 %
IMEP	(3 ± 0.12) bar	(3 ± 0.12) bar
End of injection (EOI)	-100 °CA	-300 °CA
Injection duration	0.398 ms	0.398 ms
Intake timing	-250 °CA - -170 °CA	-247 °CA - -170 °CA
Exhaust timing	160 °CA - 250 °CA	160 °CA - 248 °CA

Optical Set-Up

2-d Combustion Visualization

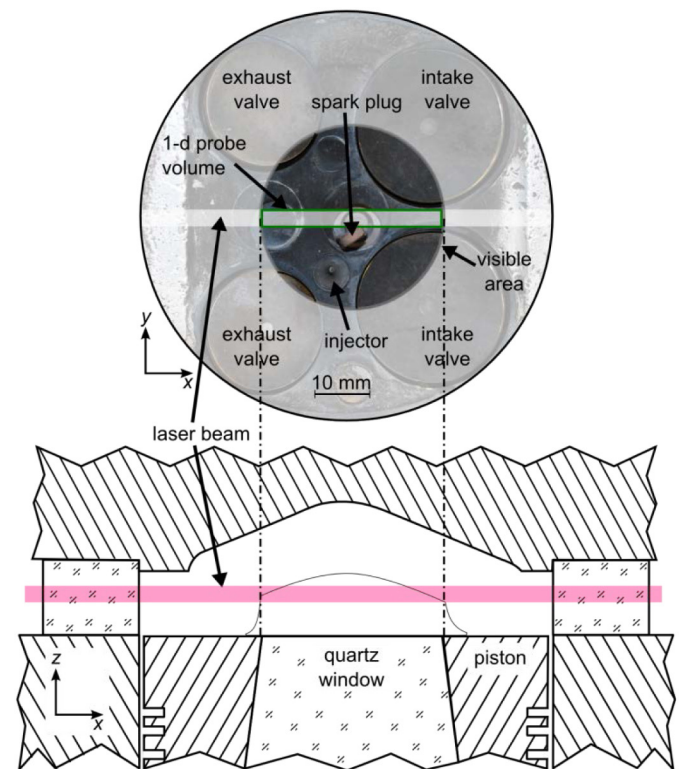


Figure 1. Combustion chamber geometry and optics. Note, that the piston has a special shape to provide the compression ratio and to avoid damage of the valves, even if they stay open around TDC, as indicated by the curved line between pentroof and piston window.

The temporal and spatial development of the Controlled Auto-Ignition combustion process is visualized by recording the 2-d chemiluminescence from hot reacting gases. For this purpose, a portion of approximately 10 % of the light from the combustion chamber is directed by a beam splitter to an intensified high-speed complementary metal oxide semiconductor (CMOS) camera (HSS6, LaVision) equipped with an 105 mm ultraviolet (UV) lens ($f = 105$ mm, $f_{\#} = 4.5$, Nikon). As shown in [Fig. 1](#), the detected signal is integrated over the vertical line of sight in the combustion chamber, because the visualization of the combustion is achieved through the transparent piston crown (diameter: 33 mm). The

gain of the high-speed image intensifier is set to about 1 % of the maximum value. The integration time of each individual “single-shot” image corresponds approximately to the frame rate of 24 kHz in the present experiment.

1-d Raman Spectroscopy

For a quantitative measurement of the stoichiometric ratio (λ), the H_2O fraction ($x_{\text{H}_2\text{O}}$), the fraction of iso-octane ($x_{\text{C}_8\text{H}_{18}}$), and the relative temperature (T) SRS is used. For this purpose, a nearly rectangular laser beam of a KrF* excimer laser (LPX 250 T, Lambda Physik) is focused by a spherical lens ($f = 2$ m). The laser-beam axis is directed perpendicularly through the central cylinder axis as shown in Fig. 1. The laser-beam focus is located several centimeters behind the engine to avoid ignition and gas breakdown in the probe area as well as damage of the window. The laser pulse energy is about 150 mJ in the probe volume and the wavelength is 248 nm. The laser is tuned between O_2 excitation lines, in order to avoid interfering laser-induced predissociative fluorescence (LIPF) emissions [45].

A 33 mm long section of the focused laser beam is imaged onto the entrance slit of an imaging spectrograph ($f_{\#} = 4$, resolution 0.1 nm) by two spherical lenses ($f = 500$ mm and $f = 200$ mm) with a demagnification of about 2.5:1. (Between the two lenses the beam splitter for the high-speed measurements is positioned.) Only 25 mm of this section can be used for SRS due to shadowing effects at the edge of the window. The scattered light passes a liquid, long-pass butyl-acetate filter in front of the spectrograph with a thickness of 10 mm to reduce the Rayleigh signal. An image-intensified charge-coupled device (CCD) camera (LaVision, 512×512 pixels with 2×16 hardware binning) is mounted in the exit plane of the spectrograph. One dimension of the CCD chip (256 binned columns) corresponds to the spectral axis while the other one (25 rows) yields spatial resolution along the imaged section.

For the stoichiometric ratio calibration, the relative SRS cross-section of iso-octane in relation to the SRS cross-section of N_2 is measured by recording SRS spectra prior to stoichiometric and homogeneous SI-combustion. Similarly, the relative H_2O cross-section is measured in the exhaust gas shortly before opening of the exhaust valves. (The results of the calibration procedure are approximately equal to those obtained from measurements done in a heatable calibration cell, described in [46].)

The spatial resolution in the direction of observation is limited by the 4 mm depth, Δz , of the laser beam. The spatial resolution along the laser beam axis of $\Delta x = 1.3$ mm is determined by the resolution of the camera due to binning. The width of the probe volume ($\Delta y = 2.5$ mm) is determined by the demagnification and the entrance slit width of the spectrograph (1 mm). The measurements are conducted about 5 mm below the cylinder head gasket (see Fig. 1), and they are conducted at -40°CA (degree crank angle with regard to TDC). A typical spectrum averaged over 30 single-shot images and the entire

1-d probe volume is shown in Fig. 2. The engine is operated under condition A, as described in the Engine Set-Up subsection. The spectrum shows that photon-statistical noise is very low due to averaging. It also indicates that there is some cross-talk of the N_2 and fuel SRS lines, which is taken into account in the data reduction procedure. Note also that the O_2 -SRS line is affected by interfering fuel and CO_2 SRS [24]. Thus, the O_2 line is not used for quantitative measurements. Rayleigh/Mie scattering is also recorded, in order to detect any possible fuel droplets. Furthermore, Fig. 2 shows that there is a broadband LIF background, which arises from intermediate combustion products in the exhaust gas, in particular polycyclic aromatic hydrocarbons (PAH) [24]. However, it is relatively weak and it increases smoothly. Thus, the interfering LIF background at the spectral positions of the SRS lines can be determined by linear regression and eliminated in this way.

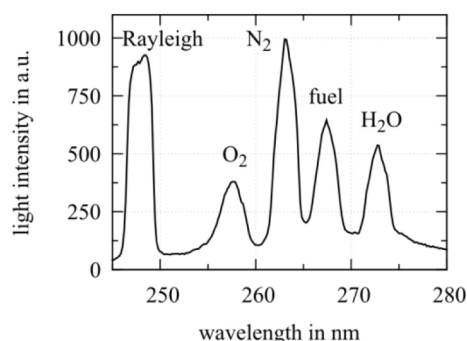


Figure 2. Laser-induced spectrum averaged over 30 single-shot images at the operating condition A.

SRS Data Reduction and Measurement Uncertainties

The intensities of the N_2 -, H_2O -, and fuel-SRS lines are determined by essentially integrating over the full line widths, in order to reduce the shot noise of the single-shot measurements. For the same reason the spatially resolved SRS signals are averaged over spatial elements with a length of 1.3 mm along the axis (x) of the 1-d probe volume. The spatial resolution of these measurements is therefore different in the three dimensions ($x \times y \times z$): 1.3 mm $\times$ 2.5 mm $\times$ 4 mm.

The temperature, residual-gas fraction, and the stoichiometric ratio are determined for each single-shot measurement before averaging, in order to avoid averaging errors [47]. The residual-gas fraction of the charge is represented by the fraction of H_2O , $x_{\text{H}_2\text{O}}$. Since the mixing of fuel, air, and residual gas is analyzed, the fraction of O_2 , x_{O_2} , can also be determined from the N_2 -, H_2O -, and fuel-SRS lines which are proportional to the densities of the corresponding species, via the calibration procedure described in the previous subsection.

The stoichiometric ratio, λ , is defined as follows:

$$\lambda = \frac{x_{\text{O}_2}}{x_{\text{O}_2, \text{min}}}$$

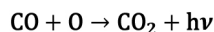
where x_{O_2} is the local oxygen concentration, and $x_{O_2,min}$ is the oxygen concentration required for stoichiometric combustion of the local fuel concentration.

Note that x_{O_2} , x_{H_2O} , $x_{C_8H_{18}}$, and λ are essentially unaffected by both window fouling and laser-power fluctuations, because they are inferred from ratios of SRS intensities. By contrast, the gas-phase temperature, which is calculated via the ideal-gas law based on the densities of all major species, depends on these factors, which affect the total light throughput of the measurements. In order to achieve low measurement uncertainties, only relative temperature data are therefore discussed in the present work (unless otherwise noted), which are calculated via the ratios of the absolute, local temperature to the absolute temperature averaged over the entire 1-d probe volume for each single laser shot. Under these conditions, the relative uncertainties (precision) of the measured charge-composition data, which are based on ratios, are dominated by photon-statistical noise (shot-noise) [32]. Thus, the precision is different for the considered quantities and data sets. Therefore, the estimated precision is shown as bars in the plots presented in the Instantaneous Mixture Composition subsection. The single-shot precision of spatially resolved measurements is generally of the order of 5 %. This is essentially consistent with previous work [45, 46, 48, 49, 50]. Accordingly, the relative uncertainty of ensemble-averaged measurements presented in the following subsection is significantly better.

Note that the absolute uncertainty (accuracy) also depends on other factors, such as the calibration procedure. However, this is not further discussed in the present article, because only trends are basically considered in the following subsections. A very similar SRS measurement system was also recently applied in the authors' lab to study (co-) evaporation of diesel-like common-rail sprays in a vessel [48, 49, 50]. More experimental details are given therein.

Emission Spectroscopy

Chemiluminescence spectra measured in an HCCI engine were analyzed in [34], using iso-octane as the fuel. Although iso-octane is regarded as a single-stage ignition fuel, an initial intermediate-temperature heat-release (ITHR) phase of combustion was identified, in which the emission appeared to be dominated by formaldehyde. However, the ITHR phase was relatively short, and its light emission was much weaker than the one observed in the following high-temperature heat-release (HTHR) phase. The latter was dominated by a broad CO continuum in the UV and visible wavelength range, which arises from the reaction



(2)

The present SRS detection system is also used for spectroscopic analysis of the chemiluminescence occurring in the GCI engine. However, a diffraction grating with 150 grooves per millimeter (instead of 1200 grooves per millimeter

for the SRS measurements) is employed in the spectrometer, in order to increase the simultaneously detected wavelength range. Note that the charge composition shortly before combustion is significantly more inhomogeneous in the present experiment as compared to the measurements in [34], as demonstrated in the Results Section. Thus, the emission spectra may be different. Significant departures from the previously obtained spectra [34] are indeed observed. For instance, three typical cycle-averaged spectra from the HTHR combustion (2 °CA, 4 °CA, and 6 °CA) are depicted in Fig. 3 (a) (the engine is operated almost under condition B as shown in Tab. 2, but with a slightly different valve timing, intake timing: -279 °CA -170 °CA and exhaust timing: 160 °CA - 279 °CA). Overall, the spectrum is dominated by the CO continuum, but considerable additional emission is observed on the short-wavelength side (< 400 nm). Thus, the peak intensity of the entire spectrum is found markedly below 400 nm, whereas it was detected beyond 400 nm in comparable studies [34, 39]. This extra emission below 400 nm can be most likely explained by both OH* and HCO*. Presumably, the strongly increased emission at about 305 nm and the weak "bump" at about 290 nm are caused by OH*. However, the long-wavelength side of the main OH* "line" at 309 nm is not resolved. It is likely swamped by HCO* emission, which is expected to be relatively strong in that wavelength range [34]. For comparison, a spectrum from conventional high-temperature combustion at -4 °CA is shown in Fig. 3 (b), in which the OH* and CH* emissions are clearly resolved (in this measurement, the engine is operated with spark ignition and homogeneous charge at $\lambda = 1$). The spectrum in Fig. 3 (b) is essentially consistent with corresponding data measured in SI engines [51, 52]. Presumably, OH and HCO emissions are more pronounced in Fig. 3 (a) compared to [34, 39], because of locally relatively fuel-rich mixture [13, 34, 52, 53].

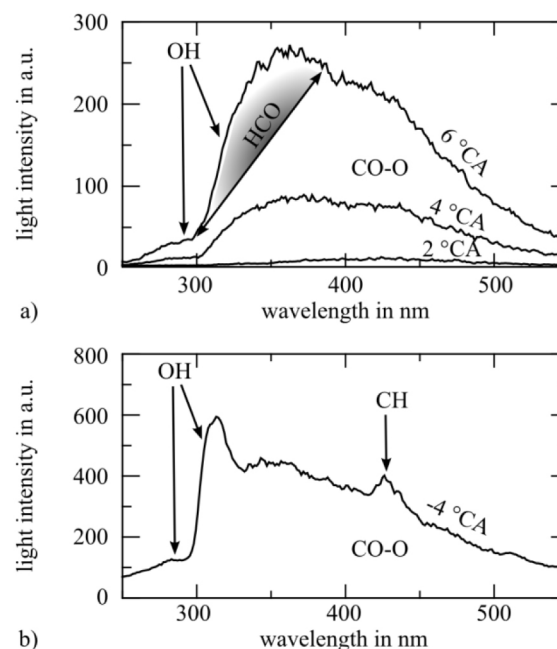


Figure 3. Typical cycle-averaged spectra from the HTHR combustion for Controlled Auto-Ignition operation at three different crank angles (a) and spark-ignition operation (b).