Combustion and emissions of controlled auto-ignition engine under stratified mixture conditions

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Abstract. Controlled auto-ignition (CAI) is an advanced combustion technology offering high thermal efficiency and low NO_X emissions. One promising approach to achieve CAI combustion is application of negative valve overlap resulting in internal exhaust gas re-circulation. However, combustion control is still an issue which should be resolved before wide application of CAI combustion. Introduction of some degree of fuel stratification via direct fuel injection is interesting approach to control combustion process.

In this study a gasoline-fuelled single-cylinder research engine was used to investigate the effects of stratification on combustion and emissions of CAI engine. The stratification was achieved using split direct fuel injection technique, where the second fuel injection controlled the degree of stratification. The results shown that variability of the second injection timing and mass of fuel injected is a viable method to control combustion on-set as well as its duration. However, the trends in both combustion and emissions were found to be non-monotonic, revealing complex relationships between mixture formation and combustion process. It has been found that small degree of mixture stratification delays combustion on-set, whereas large stratification advances combustion. The obtained results confirmed superior combustion controllability via mixture stratification, however with some limitations resulting from reduced efficiency at high degree of stratification.

1. Introduction

Controlled auto-ignition (CAI) is a combustion technique, which allows high thermal efficiency and low emissions of nitrous oxides (NO_X) as well as particulates [1]. It has been proven that CAI technology is a promising solution for automotive hybrid-electric propulsion, providing superior fuel economy and extremely low environmental impact [2].

To promote CAI combustion of gasoline-based mixture at low and partial engine loads, intake valve closing (IVC) temperatures must be largely increased. One way to create proper conditions inside a cylinder, at compression ratios typical of spark ignition engine, is heating up of the intake air [3-5]. Other approaches to elevate the thermal state of the in-cylinder charge at start of compression are based on variable valve actuation to increase the share of hot residual gasses in the mixture. Several methods are described in the literature for promoting internal exhaust gas re-circulation (EGR), including negative valve overlap (NVO) and resulting exhaust gas trapping [6-9], and exhaust rebreathing, using exhaust valve re-opening during the intake stroke [10-12].

Despite satisfactory fuel economy and emissions characteristics CAI combustion system has not been implemented yet in mass production automotive engines. The engines utilizing CAI combustion process suffer from lack of combustion on-set control. There is no direct ignition control in CAI engine. Auto-ignition is spontaneous and results almost solely from in-cylinder temperature and mixture reactivity. However, it should be noted that direct, fast-response control of reactivity and temperature inside the cylinder is not attainable. The compression temperature histories result from the amount of fresh air and its temperature, the amount of hot residuals, engine thermal state, heat losses, heat consumption for fuel vaporization etc. [3].

One way to mitigate the above drawbacks in combustion controllability is management of mixture reactivity by mixing of fuels with different auto-ignition properties. High cetane number fuel injected early in the compression stroke can partially premix with low cetane fuel mixture, creating a reactivity gradient [13]. Such dual fuel concepts, referred to as reactivity controlled compression ignition allow for maintaining low temperature combustion dominated by reaction kinetics, adding additional, fast controllability with injection timing and blend ratio [14]. This combustion concept has been intensively investigated in recent years, on variety of different fuels [15-17]. Most of the works showed potential in reaching higher than baseline diesel thermal efficiency and ultra-low NO_X emissions [15].

It should be also noted that combination of exhaust gas trapping using the NVO technique and direct fuel injection can provide control of the mixture reactivity using single fuel. Injection of a certain portion of fuel during exhaust recompression enhances exhaust-fuel chemical reactions which produce substantial amount of acetylene and other auto-ignition promoting species [18,19]. This approach can help in widening of the low load engine operating range [20,21]. The mixture reactivity can be varied via amount of fuel injected and injection timing during NVO [18,22]. However, the primary benefit of direct gasoline injection as such is creating a partially stratified mixture. Mixture stratification has been considered in numerous studies to control combustion harshness at high load CAI operation [23,24].

In the current study both the aforementioned methods were utilized to control CAI combustion in a gasoline fuelled engine. Split fuel injection was applied, where one fuel dose was injected into retained residuals to achieve fuel reforming, whereas another portion of fuel was injected late to stratify the mixture. This approach allowed the authors to achieve stable CAI combustion at low engine load in parallel with auto-ignition timing control via fuel stratification. However, the effects of fuel stratification turned out to be complex non-linear phenomena.

2. Methods

2.1. Research Engine and Measurement Instrumentation

The research was performed on a single-cylinder engine equipped with a hydraulic-based variable valve actuation system, enabling NVO operation. The fuel was introduced with a side mounted, single-stream, swirl-type injector directly to the bowl-shaped combustion chamber located in the cylinder head. The main engine parameters are specified in table 1. For further details on the valve actuation system and piston-injector alignment consult earlier works by Hunicz et al. [25,26]. Note that all crank angle (CA) parameters are given in orientation as in figure. 1.

The engine was installed on a test stand with a direct current dynamometer. The control system was based on an in-house software installed on a computer, which facilitated both dynamometer and engine (air-path, all media) control. The same computer, connected with a real-time timing module governed injector and ignition coil actuation.

The engine test bench was equipped with a following measurement equipment. The intake airflow and fuel consumption were measured with a thermal mass flow meter and fuel balance respectively. The engine was instrumented with a set of pressure and temperature transducers in order to control the thermodynamic conditions of all media; intake, exhaust, cooling liquid, etc. In-cylinder pressure was recorded with a head-mounted pressure transducer connected via a charge amplifier to the data acquisition system. The indication was triggered by an optical encoder with a constant crank angle resolution of 0.1°CA. Exhaust gas emissions were measured using an AVL Fourier transform infra-red gas analyzer. Typically, after stabilized engine conditions were reached, a constant time window of 30 s was applied for emission recording at each operating point.

Table 1. Research engine specifications.

Parameter name	Value
Displacement	498.5 cm^3
Bore	84 mm
Stroke	90 mm
Compression ratio	11.7
No of valves	2
Intake valve open/close	85/215 °CA
Intake valve lift	3.6 mm
Exhaust valve open/close	521/640 °CA
Exhaust valve lift	2.9 mm

2.2. Experimental Conditions and Procedure

The research was conducted at constant crankshaft rotational speed of 1500 rev/min, with the focus on low load operation (around 2 bar IMEP), as particularly challenging for gasoline auto-ignition controllability. The temperature of the cooling liquid at the engine outlet was maintained at level of 90°C +/- 1. The engine was operated as naturally aspirated and with fully open throttle. The average intake temperature was kept at the level of about 40 °C. The engine was operated in the NVO mode and reduced lifts of the valves (see table 1) which resulted in high amount of retained exhaust. The engine was fuelled with Euro Super commercial gasoline with research octane number of 95. The fuel was injected directly to the cylinder in two portions. The first fuel dose was injected 40 °CA bTDC (before top dead centre) during the NVO period to provide premixed mixture and enable reforming. The second fuel dose was injected with variable start of injection (SOI) timing. Additionally, three different split fuel ratios were applied, with 50%, 65% and 80% of fuel mass injected later. Excess air ratio (λ) was kept constant at level of 1.24 via corrections of injection duration of the second dose. The rate of internal EGR, expressed as a ratio of mass of trapped residuals to the entire in-cylinder mass during the main event, was approximately 0.55. It should be noted however that all aforementioned parameters besides λ, which was actively controlled, were varying because of the thermal effects of variable injection strategies and combustion timing, and its completeness. These effects further have an impact on the balance between the mass of aspirated fresh air and the mass of trapped residuals, and finally on IMEP and thermal efficiency, as shown in the next section.

2.3. Data Analysis

The analysis of combustion evolution was performed with the use of AVL BOOST software on the basis of the measured pressure traces. Net heat release rate (HRR) was computed using the first law of thermodynamics in the form shown in equation (1):

$$\mathrm{HRR} = \frac{\gamma}{\gamma - 1} p\, dV + \frac{1}{\gamma - 1} V\, dp, \tag{1}$$

where p was in-cylinder pressure, V was volume above a piston, and the ratio of specific heats γ was computed according to instantaneous temperature and mixture composition in the cylinder. The mass fraction burnt (MFB) was computed as a standardized integral of heat release. To calculate combustion duration, the angular distance between 5% MFB and 95% MFB was considered. Combustion timing was expressed as location of 50% MFB. Indicated mean effective pressure (IMEP), which express the engine ability to do work, was calculated as a ratio of thermodynamic work and the cylinder swept volume. The BOOST software accommodated also mass flow model, which enabled estimation of the mass of trapped residuals. More information on 0-dimensional engine modeling using measured in-cylinder pressure can be found in [27]. The raw exhaust gas composition results (concentrations on the volume basis) were time averaged and recalculated using indicated power and exhaust mass flow to the mass per indicated work basis.

3. Results and discussion

3.1. Combustion analysis

Figure 1 presents the whole engine cycle in-cylinder pressure trace for different split ratios and secondary injection timings. The crank angle values of 0 °CA and 720 °CA refer to the TDC during NVO. Analysing the pressure signal it is noticeable that the effect of the investigated injection strategies on the combustion process is meaningful. With early injection of fuel during NVO phase (SOI = 20 °CA) it is assumed that the mixture is fully homogeneous during the main event. With this point taken as reference, one can note that the direct, main event injection aimed for achieving fuel stratification, have different effect on combustion phasing depending on the SOI. For SOI = 240 °CA the combustion starts slightly later than for the reference, whereas for SOI = 300 °CA the combustion is advanced. Furthermore, for both cases increasing the split ratio from 50% to 80% retards the combustion.

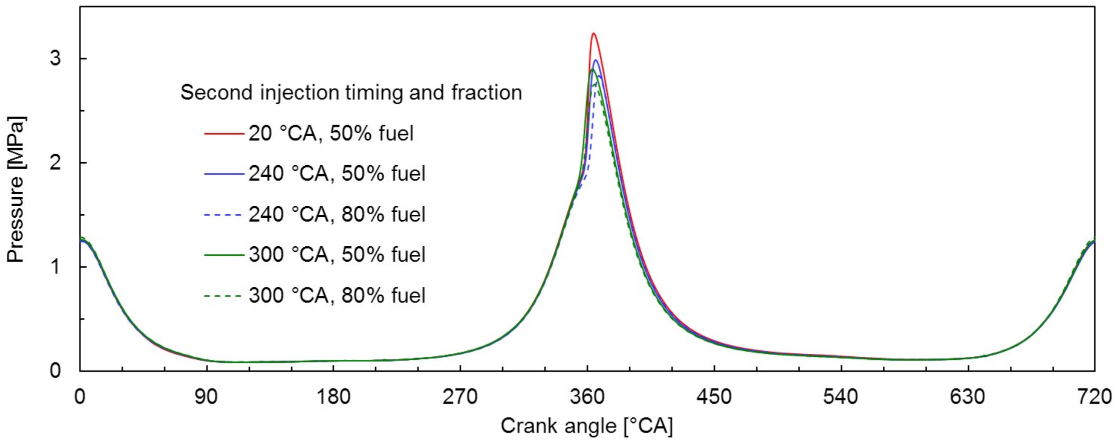

Figure 1. In-cylinder pressure for all investigated conditions.

In order to further investigate the trends in combustion and emissions associated to mixture stratification, more extensive SOI sweeps were performed and discussed on the basis of individual combustion indicators (IMEP, thermal efficiency, percent of MFB, combustion duration).

Figure 2 shows overall engine load expressed as IMEP. One should know that the present experiments were performed at very low load, which is a boundary regime for CAI operation [28]. At this load level it is necessary to inject some portion of fuel during exhaust re-compression to utilize its reforming and increase both mixture reactivity and temperature, as NVO reactions produce heat [29,30].

Figure 3 shows that independently from SOI of the second fuel dose, there is a meaningful difference in thermal efficiency for different fuel split ratios. In general, the more fuel injected in the second phase, the higher the efficiency. It can be ascribed to partial fuel oxidation during the NVO period, which reduce work produced during the main event combustion.

The trends in IMEP versus SOI are similar for all split fuel ratios, as shown in figure 2. In general, when the second fuel injection is applied during NVO exhaust expansion (i.e. before 85 °CA), delay in SOI increases IMEP by approximately 10%. Comparison of figure 2 with figure 3 indicates that this trend in IMEP results mostly from efficiency. In the largest extent the changes in efficiency result from the changes of work performed by the system during exhaust expansion. The reason for this behaviour is angular location of fuel vaporization. Simply, early NVO injection (but after NVO TDC) reduces exhaust expansion work, because of early pressure drop due to fuel vaporization. Instead, at late injection heat is absorbed during intake process, and does not affect indicated work. Furthermore, the reduced intake temperature, improves fresh air aspiration. As a result, delay of second SOI towards 85 °CA increases overall fuelling by 2-3% for lambda control, which contributes to the observed IMEP increase.

One can note that for SOIs between 85 °CA and 170 °CA, which covers the main part of the intake phase, the efficiency and IMEP are nearly constant for the given split ratios. During this period the intake velocities are sufficiently high to promote good mixing towards well homogenized in-cylinder composition. For SOIs around 170 °CA a transition phase is clearly visible. Despite the intake valve remains open until 215°CA, the pressures in the cylinder and in the manifold have already stabilized causing the intake invoked turbulence to quench rapidly. Beyond this point, IMEP values start to gradually decrease with SOI, which is attributed to increased role of fuel stratification. This is further discussed basing on the combustion phasing and combustion duration plots presented in figures 4 and 5 respectively.

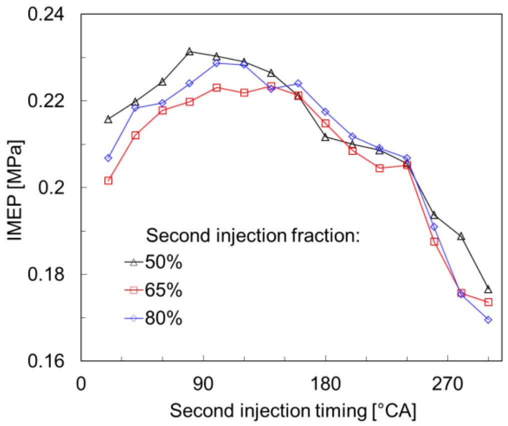

Figure 2. Indicated mean effective pressure (IMEP) with respect to second injection timing.

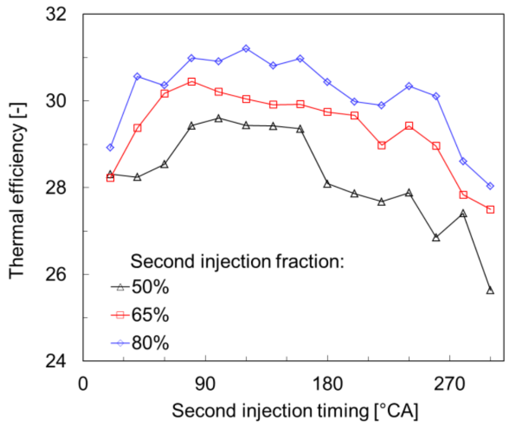

Figure 3. Thermal efficiency with respect to second injection timing.

Figures 4 and 5 show high sensitivity of the combustion timing to the applied injection strategy. For NVO injections, the shift of the location of 50% MFB by 3 °CA can be achieved, in the tested conditions, with SOI variation. This is associated with increase in combustion duration by less than 1 °CA, and caused by the mentioned thermal and chemical effects of fuel reforming during NVO. For further details on those effects and their implications on engine operation the reader is referred to the works [9,20,21,25]. The discussed insensitivity region for SOIs during the intake phase (i.e. for SOIs between 85 °CA and 170 °CA) is also visible. This is coherent with the observations based on performance parameters analysis (figures 2 and 3) and confirms the assumption on mixture homogeneity in this regime.

Despite the exact fuel pattern during the spray evolution is impossible to determine without detail CFD simulations or optical engine research, it can be assumed basing on figures 2-5 that the in-cylinder stratification is created for SOIs larger than 170 °CA. Despite the intake valve remains open until approximately 215 °CA the in-cylinder and manifold pressures have already equalized, and the intake invoked turbulence rapidly quenches. Starting from 170 °CA further retarding the SOI causes the fuel to be less and less homogenized in the main event, resulting in combustion duration increasing gradually (figure 5) This is understandable since the combustion does not happen volumetrically as for homogeneous case, instead multiple ignitions sources are created at various times across the cylinder volume. Interestingly, the trends in 50% MFB are not monotonic for increased fuel stratification. The Combustion phasing is first prolonged (up to 3 °CA shift for the highest, 80% split ratio) and starting from SOI around 225°CA, the 50% MFB point shifts back towards TDC, as shown in figure 4. The mechanisms responsible for such behaviour are complex and influenced both by the local equivalence ratio (resulting in a mixture to be either bellow or above optimum ignitibility point) and its spatial distribution (richer mixtures forming closer or further from the cold/hot cylinder surfaces that can either act as combustion inhibitors or ignition sources). The further explanation of this phenomena is especially difficult for the present experimental setup, where non-symmetrical effects associated to side-mounted injector play significant role, and excides the framework of this short communicate.

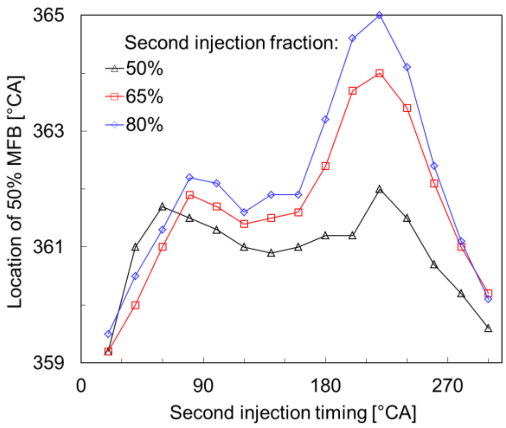

Figure 4. Location of 50% mass fraction burnt (MFB) with respect to second injection timing.

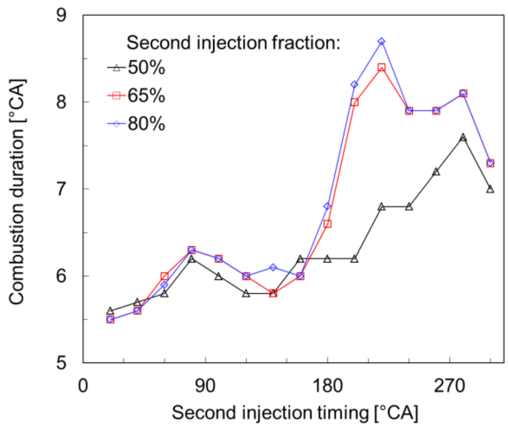

Figure 5. Combustion duration with respect to second injection timing.

3.2. Emission analysis

The trends in exhaust emissions, expressed as indicated specific values reveal effects of stratification on combustion. In general, emission of CO, shown in figure 6, increases with increased fuel stratification, however without significant effect of split fuel ratio. In contrast, emissions of unburnt HCs, shown in figure 7, are reduced for highly stratified mixture. The trade-off between CO and HC emissions could be explained as follows. Late injection and resulting stratification creates local zones of fuel-rich mixture, which produce CO. At the same time the directly injected fuel is concentrated in the central part of combustion chamber. As a result, side-wall effect and crevice effect, which are primary sources of HC emissions, are significantly reduced. It should be noted that the opposite trends in HCs and CO emissions result in similar combustion efficiency levels, calculated on the basis of exhaust compositions. Thus, the changes in thermal efficiency, shown in figure 3, are resulting solely from NVO thermal effects and combustion timing.

Figure 8 shows interesting behaviour of NO_X emissions. In fact, NO_X emissions are almost constant for all investigated conditions. This is caused by two counteracting mechanisms. From one side increased stratification is responsible for appearance of locally hot regions during combustion. From the other side as suggested by figure 6, in the same regions local oxygen availability decreases significantly. With NO_X creation rates being inversely dependent on temperature and oxygen concentration, this explains why no significant changes have been observed. On the other hand, note that the recorded NO_X emission levels are ultra-low (typical for low temperature combustion concepts) and close to measurement accuracy limits (approximately 20 ppm on the volume basis).

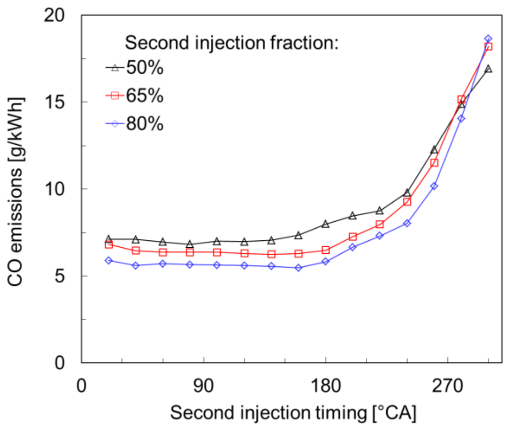

Figure 6. Emissions of CO with respect to second injection timing.

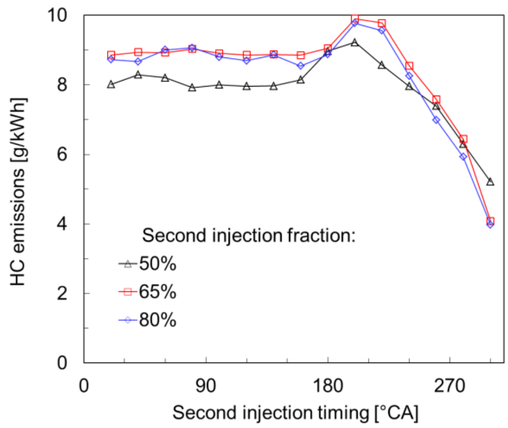

Figure 7. Emissions of unburnt HCs with respect to second injection timing.

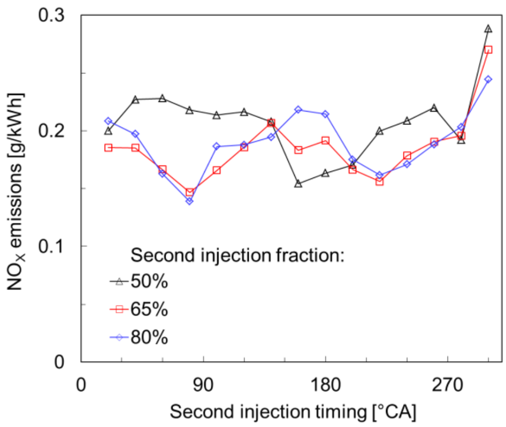

Figure 8. Emissions of NO_X with respect to second injection timing.

4. Conclusions

The work reveals important effects of divided dose, direct injection strategy on controlled auto-ignition gasoline engine operation at low loads. This includes characterization of engine combustion, performance and emission indices. Particular emphasis is applied on identifying the boundary conditions for homogeneous and partially stratified combustion. For the analysed operating point observable stratification effects are seen for fuel split ratios above 50% and SOI higher than 170 °CA which covers the late part of the intake process and closed part of the cycle.

Further on, the effects of increased stratification, achieved via regulating the SOI and split ratio has been investigated. Main observations are as follows:

- Increasing the stratification (retarding the SOI or increasing split ratio) results in prolonged combustion which can have negative impact on engine efficiency if not mitigated by other means (IVC temperature, thermal effects of NVO injection).
- Retarding the second dose SOI towards increased fuel stratification decreases THC and simultaneously increases CO emissions. The overall combustion efficiency remains on the same level. Emissions appears to be insensitive to split ratio change and NO_X concentration is additionally insensitive to any of the tested stratification measures.
- Increasing the split ratio, at the set SOI within the stratification regime, retards the combustion. The effect is strongest for SOI = 225 °CA and decreases while shifting the injection in both directions from this set point. At the same time, the effect of SOI on

combustion phasing is non monotonic, with the inflection point located around the mentioned value of 225 °CA.

The present work, despite clearly focused on experimental identification of the effects of fuel stratification on CAI engine operation, provides suggestions on the phenomena governing the observed trends. Yet, detail understanding and quantification of those phenomena, requires more in-depth study with specific tools enabling the insight on fuel stratification inside the cylinder.

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