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REDUCTION OF PRESSURE RISE RATES IN BOOSTED HCCI ENGINE USING ADVANCED VALVE ACTUATION STRATEGIES

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Abstract

Homogeneous Charge Compression Ignition (HCCI) is a promising low temperature combustion technology which offers high fuel efficiency and extremely low exhaust emissions. However, there are still some pending issues to be resolved before the technology will achieve mass production level. Namely, combustion controllability should be improved and HCCI operating range should be widen. The latter is constrained by excessive combustion rates under high loads. In this study, advanced variable valve actuation strategies were applied to control auto-ignition timings and combustion rates. The examinations were conducted using single-cylinder research engine fuelled with directly injected gasoline. The HCCI combustion was achieved using negative valve overlap technique. The engine was run under boosted conditions, in an operation regime where acceptable pressure rise rate (PRR) level is usually exceeded. Selected valve timing sweeps were carried out within a scope of the experiments to evaluate PRR reduction potential. The obtained results manifested superior combustion controllability. Late exhaust valve closing enabled reduction of the amount of internally re-circulated exhaust, which propagated to the main event combustion. From the intake side, two effects were observed, i.e. variability of the intake air aspiration and variability of the apparent compression ratio. Both phenomena were found to affect combustion timings and rates.

Keywords: *low temperature combustion, HCCI, valve actuation, combustion harshness*

1. Introduction

Propulsion systems in transport have been undeniably dominated by internal combustion engines. The general trend towards increased efficiency and environmental neutrality makes it necessary to conduct further research to meet the expectations. Among the widely studied advanced combustion concepts, the implementation of low-temperature combustion in homogeneous charge compression ignition (HCCI) engines deserves special attention. It is currently the most beneficial technology, which is characterized by extremely low emissions of Nitrogen Oxides (NO_X) and particulates as well as high thermal efficiency [15].

The wide application of combustion engines using HCCI technology is however constrained by a number of factors that prevent their commercial use. The combustion process, depending only on the rate of chemical reactions, is very fast which causes a high-pressure increase and combustion noise while increasing the engine load. It limits the use of HCCI technology to work only in the low load range [11]. Another limitation is the lack of direct control on the moment of ignition. Only the temperature inside the cylinder and the reactivity of the mixture determine the auto-ignition [5]. However, it should be emphasized that there is no possibility of direct control over the reactivity and temperature inside the cylinder. The value of the compression temperatures depends on such factors as the amount of fresh air and its temperature, the amount of captured exhaust gas and the temperature of the exhaust, thermal condition of the engine, heat loss, heat consumption to evaporate the fuel, etc.

The trapping of hot exhaust gases with NVO technology is one of the research approaches to achieve stable HCCI operation. As a result of using the NVO technique, it becomes possible to achieve the auto-ignition temperature of gasoline-like fuels with relatively low compression ratios

[6]. In addition, internal exhaust gas recirculation (EGR) is implemented. Engine control strategies with variable timing are the subject of numerous studies. The dependence of the quantity of aspirated fresh air and trapped residuals from the valve timing has been proven. Variable exhaust valve closing (EVC), allows effective control of the amount of trapped residuals, also with the influence on the fresh air aspiration [9].Variable intake valve timings control the aspiration of fresh air. It additionally has an impact on the turbulence in the cylinder [7]. Finally, the variable intake valve closing (IVC) is a method of controlling the apparent compression ratio. However, the engine operation in the NVO mode is limited to the low load range and is penalized by increased thermal losses of exhaust recompression [13].

The variable valve actuation (VVA) enables the implementation of negative valve overlap (NVO) strategy in the low- and medium-range engine load and switching to conventional valve timings in the rest of the engine operating area. However, the area of HCCI operation should be widen to improve overall efficiency of the dual combustion mode engine. It can be achieved using intensive boosting. However, the problem of very fast heat release and high energy density at elevated engine loads, which may cause excessive peak in cylinder pressures and unacceptable pressure rise rates (PRR), remains unresolved [12]. Therefore, the extension of the working range at high loads of HCCI engines, taking into account excessive emissions and the harshness of combustion requires further research.

The delayed auto-ignition and prolonged burning time allow reducing the PRR. Decreasing the inlet temperature allows achieving the former, while the latter determines only the chemical kinetics [12]. If there is no possibility to manage the inlet temperature there are many other ways to reduce the PRR; use of extremely diluted mixtures, achieved due to high boost pressure, increase in EGR, reduction of apparent compression ratio [10], formation of a stratified mixture [4], control of reactivity of the mixture using dual fuel combustion [8] or reforming of fuel in the cylinder [1, 14].

The recent work by the authors of this study [3] proved that application of boost indeed enables increase of attainable engine load. However, acceptable combustion harshness levels were exceeded, where indicated mean effective pressure (IMEP) values were higher than 0.5 MPa. To reduce this parasitic effect, late fuel injection was found to be a viable method to reduce PRRs. The reason for this was stepwise combustion of stratified mixture, which finally extended combustion duration. It has been found, however that boost pressure advanced auto-ignition that negatively contributed to the combustion harshness. The present study demonstrates effects of valve actuation strategies to delay auto-ignition and thus reduce combustion harshness under boosted HCCI combustion using NVO strategy. Variable intake and exhaust valve timings enabled control of start of compression temperature, and thus optimal shaping of the HRR curve.

2. Experimental set-up

A single-cylinder research engine was installed on a test bed equipped with a DC dynamometer. The engine was equipped with a fully variable valvetrain with independent regulation of valves lifts and timings. The regulation of valves lifts was relied on a hydraulic mechanism. The fully variable valvetrain provided internal EGR with the use of the NVO technique. The engine was equipped with mechanical boost device, providing controlled intake pressure.

The research engine had a bowl-shaped combustion chamber located in the engine head. The piston face was protruding on its perimeter and approached the cylinder head closely at TDC, which generated some amount of squish. Fuel was applied into the cylinder with the use of a side-mounted single-stream swirl-type injector. The main engine parameters are specified in Tab. 1. All crank angle parameters are consistently given in orientation as in Fig. 1, where 0 is top dead centre (TDC) during the NVO period, and 360 °CA is TDC during the main event.

The engine control was realized using in-house computer software combined with a real-time timing module, which regulated start of injection angles and injection durations. However, at each operating condition, all control parameters, with the exception of engine thermal conditioning and rpm control, have been set constant.

Tab. 1. Research Engine Parameters

Parameter	Value
Displacement	498.5 cm^3
Bore	84 mm
Stroke	90 mm
Compression ratio	11.7
No. of valves	2
Intake valve open (IVO)	-277 °CA
Intake valve close (IVC)	-147 °CA
Intake valve lift	3.6 mm
Exhaust valve open (EVO)	167 °CA
Exhaust valve close (EVC)	-434 °CA
Exhaust valve lift	2.9 mm

All the necessary measuring and control instruments were installed on the test bench. Fuel consumption was measured using a fuel balance, while a thermal mass flow meter was used to measure the inlet airflow. In order to control the thermodynamic conditions of inlet air, oil, cooling liquid, etc. the engine has been equipped with a set of pressure and temperature transducers. A miniature AVL GH12D pressure transducer mounted directly in the engine head was used to measure cylinder pressure.

At each operating condition, the in-cylinder pressure was recorded for 100 consecutive cycles with angular resolution of 0.1 crank angle (CA) degree. The pressures traces were then ensemble averaged. The in-cylinder pressure data were analysed using AVL BOOST software. As a boundary condition for thermodynamic gas exchange and combustion models, the measured pressure values were used. The temperature inside the cylinder was calculated using the ideal gas state equation as the average value for the entire volume of the combustion chamber. The net heat release rate (HRR) was calculated in accordance with the first law of thermodynamics.

The experiments were performed at constant rotational speed of the engine set to 1500 rpm without throttling. The engine was boosted to intake pressure of 0.145 MPa absolute. The engine was fuelled with European Euro Super commercial gasoline with a research octane number of 95. Fuel injected directly into the cylinder was split into two parts. The first start of fuel injection (SOI$_1$) was set to 60 °CA bTDC, and the second injection (SOI$_2$) was commenced 90 °CA a TDC. All experiments were performed at fixed injection durations, providing a total amount of fuel approximately 19.5 mg per cycle.

The experimental matrix comprised of intake valve opening (IVO) and EVC sweeps around baseline NVO setting, i.e. the EVC and IVO placed symmetrically at 80 °CA before and after NVOTDC respectively. At one valve’s timing fixed in the reference point, the second one was advanced or retarded. The reference condition was selected to have the highest attainable thermal efficiency. The other valve train parameters were set to lay on the boundary level of cycle-by-cycle variability (5% coefficient of variation in IMEP). All the examined valve timings are illustrated in Tab. 2 and Fig. 1.

3. Results and discussion

The commonly accepted limit for combustion harshness expressed by PRR at 1500 rpm is 0.5 MPa/°CA [11]. For reference conditions, this limit was highly exceeded, as shown in Tab. 2. Tab. 2 also shows how effective are different valvetrain strategies in reducing PRR.

The most impactful valvetrain setting appeared to be (late exhaust timing) LE case, which effectively reduced PRR, far below the threshold value. All other valving strategies also reduced PRR, however, in much lower extent. It should be noted that all the valvetrain settings applied in this study, except the reference conditions, were laying on the boundary of the acceptable engine-operating map. Thus, further reduction of PRR was associated with the increase of cycle-by-cycle variability. It should be also noted that for given amount of chemical energy introduced with the fuel, PRR could be reduced solely by an increase of combustion duration and/or by a delay of auto-ignition.

Tab. 2. Valvetrain settings and main engine operating parameters

Case	EVO [°CA]	EVC [°CA]	IVO [°CA]	IVC [°CA]	NVO [°CA]	IMEP [MPa]	PRR [MPa/°CA]
Reference (Ref)	-199	-80	80	210	160	0.546	0.78
Early Exhaust (EE)	-211	-92	80	210	172	0.522	0.68
Late Exhaust (LE)	-193	-74	80	210	154	0.524	0.24
Early Intake (EI)	-199	-80	64	194	144	0.524	0.74
Late Intake (LI)	-199	-80	89	219	169	0.542	0.61

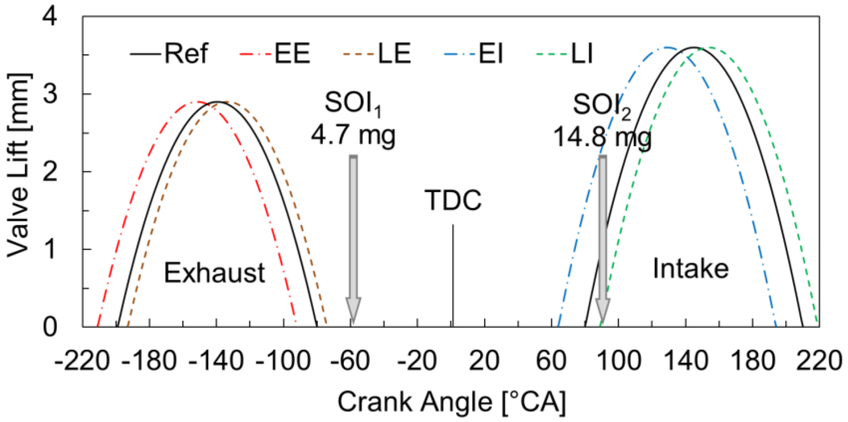

Fig. 1. Intake and exhaust valve lifts applied in the study. Symbols of valvetrain settings are explained in Tab. 2

Fig. 2 shows in-cylinder pressure for all investigated conditions. Without any detailed analyses, it can be noted that valvetrain settings have a great influence on combustion evolution. As already mentioned, the most effective approach was LE strategy. Interestingly, early exhaust valve timing (EE) strategy advanced combustion; however, the effect was much lesser than in the case of valve timing delay. It should be noted that besides advanced auto-ignition, PRR was slightly reduced with comparison to reference conditions, as shown in Tab. 2. Both, early and late intake valve timings delayed combustion. However, careful analysis of the pressure curves in Fig. 2 reveals that end of compression pressures vary in a high extent. It suggests that mixture compositions substantially differ, which influence thermodynamic properties of the working fluid.

The temperature curves, shown in Fig. 3, support the thesis that auto ignition timing is primarily determined by compression temperature histories. It is clearly visible that the higher the end of compression temperature, the earlier the auto-ignition. It should be also noted that peak in-cylinder temperatures are different, and the observed differences are not the effect of solely pressure and volume. Namely, valvetrain settings control a degree of fuel dilution by air and trapped residuals. Moreover, the proportion between mass of aspirated air and exhaust gas affects specific heats of the in-cylinder load.

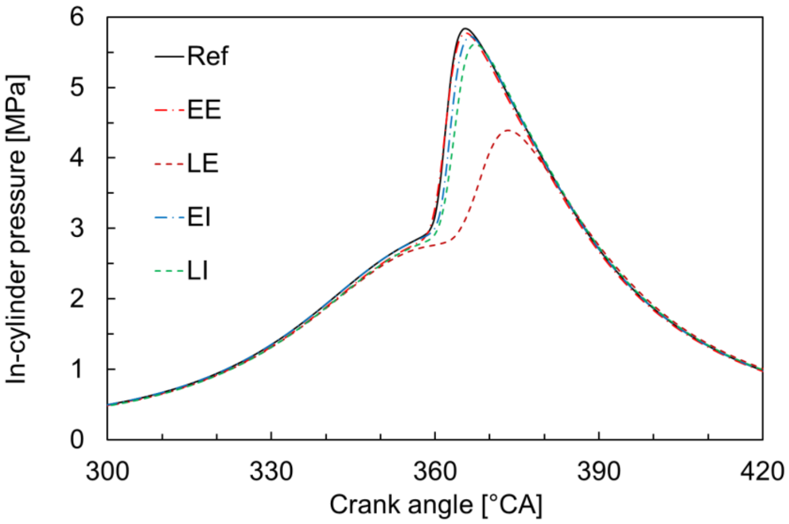

Fig. 2. In-cylinder pressure for all investigated conditions

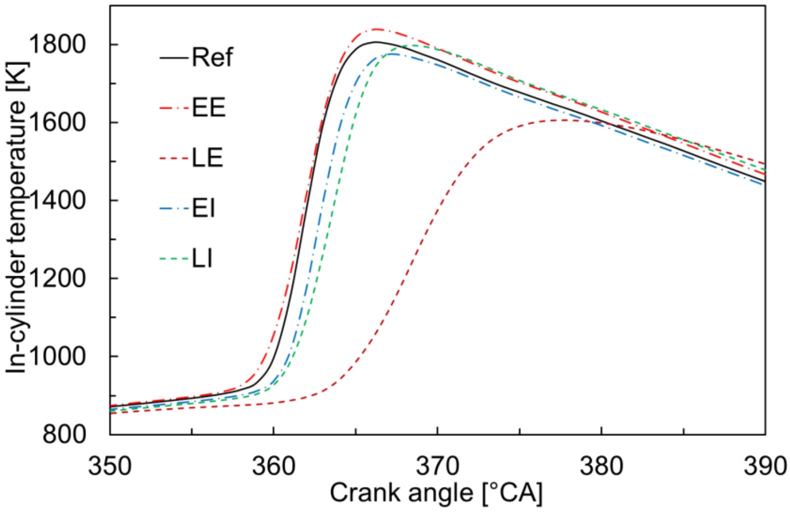

Fig. 3. Calculated in-cylinder temperature for all investigated conditions

More detailed data on combustion evolution can be provided by analysis of the HRR curves, shown in Fig. 4. EE valvetrain strategy indeed advanced auto-ignition; however, end of combustion timing was the same as for reference conditions. It is plausible, because increase the amount of trapped residuals elevated compression temperature, as shown in Fig. 3, but simultaneous increase of the internal EGR fraction reduced reaction rate. Variations of the intake valve phase in two directions from the reference setting result with delay of auto-ignition to the same location. It is interesting, however that the two opposite strategies have different impacts on combustion duration. Late intake valve timing (LI) strategy prolongs combustion duration in comparison to early intake (EI) strategy.

To analyse in details the complex effects of valve actuation strategies it is necessary to consider all parameters affected by valve opening and closing events like mixture composition and its amount, thermodynamic properties as well as thermodynamic compression ratio. It is commonly acknowledged that increase of temperature advances auto-ignition, whereas EGR rate increases combustion duration [5]. It should be also noted that during the current research the mass of fuel was fixed, thus valvetrain settings affected excess air ratio. The latter have also impact on the mixture propensity to auto-ignition. Under the same thermal conditions leaning the mixture retards auto-ignition [2].

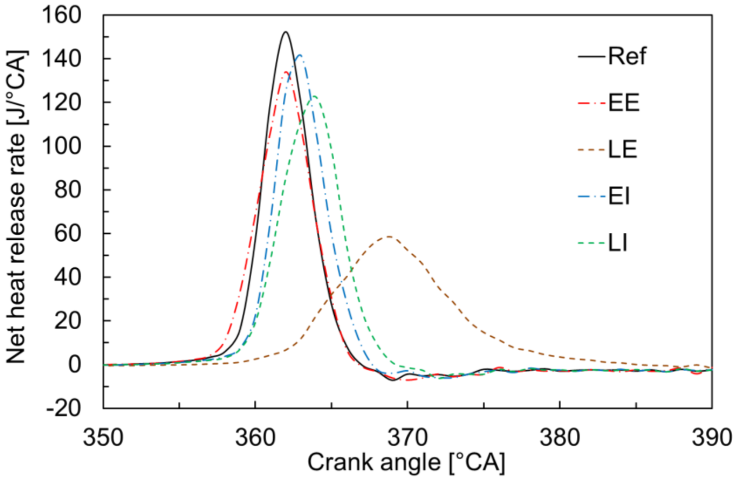

Fig. 4. Calculate net heat release rates for all investigated conditions

Fig. 5 shows all the available parameters that affect auto-ignition timing and combustion duration. The parameters were presented as a percentage change in relation to the reference conditions. Additionally, at the bottom of the graph there are provided shifts of 5% MFB. The effect of LE strategy appears to be obvious. Reduction of the mass of the trapped residuals and increase the mass of aspirated air reduce IVC temperature. As a result, 5% MFB is delayed by 5 °CA. Opposite shift of the exhaust valve timing increases amount of trapped residuals to a high extent. At the same time mass of aspirated air is reduced which results in high increase of start of compression temperature. Keeping in mind that for both EE and LE strategies intake valve timing was the same as for reference conditions, higher advance of auto-ignition in the EE case would be expected. However, in the EE case mixture propensity to auto-ignition was reduced, plausibly because of largely increased EGR rate.

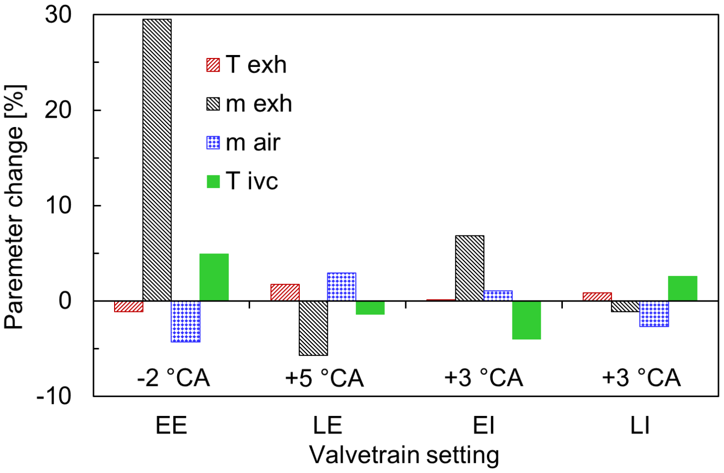

Fig. 5. Relative change of parameters affecting combustion timing at variable valvetrain settings

Analysing intake valve timing effect, another important factor should be considered. Namely, IVC event controls thermodynamic compression ratio. Thus, two opposite effects were observed at intake valve timing variations. EI strategy provided substantial reduction of the IVC temperature, providing only 3 °CA auto-ignition delay effect. For LE strategy, auto-ignition was much more delayed at higher IVC temperature. However, as already noted EI strategy increased thermodynamic compression ration from 11.13 at reference conditions to 11.58 at the analysed point. As a result, end of compression temperature was less reduced that one resulting from IVC conditions solely. One observation that is more important should be made according to EI case. Drop in IVC temperature was observed despite increase of EGR rate at exhaust temperature the same as at reference conditions. This behaviour can be ascribed to cooling effect of the early backflows, which are inevitable at such early intake valve opening. This effect was already investigated and quantified by [16]. For LI strategy auto-ignition is delayed besides increase in the IVC temperature. In this case, however compression ratio was reduced to 10.75, which delayed ignition due to lower end of compression temperature, as shown in Fig. 3.

4. Summary

The current study explored the potential of various valve-timing strategies to reduce combustion harshness in a boosted HCCI engine. It has been found that the end of compression temperature is the sole factor determining the auto-ignition delay. Combustion duration, which even more affects PRR, was however affected by numerous mixture parameters. The results of the study are summarized below. All findings are presented in relation to baseline valvetrain setting, i.e. symmetrical EVC and IVO providing NVO period of 160 °CA.

1. Delay of exhaust valve timing, which decreases of the amount of trapped residuals, has the greatest potential to reduce PRR. This strategy reduces start of compression temperature and additionally increases excess air at fixed fuel dose. The latter affects both auto-ignition delay and reaction rates.
2. Advance of exhaust valve timing, although increases mass of trapped residuals, also reduces combustion harshness, however in much lesser extent. In fact, increase of the mass of trapped residuals advances combustion, but it also reduces combustion rates.
3. Advance of intake valve timing increases the mass of exhaust, however reduces start of compression temperature under the same exhaust temperature. This peculiar effect is ascribed to cooling effect of early backflows. However, the delay of auto-ignition is lower than for late exhaust case besides higher temperature reduction. It is an effect of increased thermodynamic compression ratio.
4. Delay of the intake valve timing provides the same combustion timing as the opposite shift, besides much higher start of compression temperature. This is the effect of reduced compression ratio. This strategy also extended combustion in comparison to advanced intake valve timing.

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