

Characterisation of the Combustion Process in the Spark Ignition and HCCI Engine Fuelled With Methane

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ABSTRACT

Homogeneous Charge Compression Ignition (HCCI) engine is a potential solution for reducing air pollution and for satisfying legal limits of permissible emissions from internal combustion engines (ICE). Combustion process in HCCI engine is a form of Low Temperature Combustion (LTC) that has a potential of achieving high efficiencies.

HCCI engines have advantages of lower emissions of nitrogen oxides (NO_x) and particulate matter (PM), compared to standard combustion modes, but on the other hand one of the major disadvantages is the fact that it is relatively difficult to control a start of combustion because it is highly sensitive to the intake air temperature. Additionally advantage of the HCCI engine is the ability to operate with variety of fuels. Therefore in this study HCCI engine is powered by methane.

The aim of the study is to characterise and compare two different combustion modes on the same engine at similar operating conditions. To perform such characterisation the engine tests are performed at the same indicated mean effective pressures (IMEP) for the spark ignition (SI) and HCCI combustion mode at the same engine speed. Load for the HCCI engine was adjusted by setting the appropriate air to fuel ratio while for the SI engine, predefined load (IMEP) was obtained by changing the intake air pressure. The tests are performed at three different speeds and three different levels of IMEP on the experimental setup built in the Laboratory for IC Engines and Motor Vehicles at the Faculty of Mechanical Engineering and Naval Architecture. The setup consists of modified single cylinder diesel engine Hatz 1D81Z and the modifications have enabled operation in SI and in HCCI mode. The characterisation includes the comparison of in-cylinder pressures, temperatures and rate of heat release (ROHR) obtained by SI and HCCI combustion mode. It also presents comparisons of the emissions of HC, CO, CO₂ and NO_x, and in the end the comparison of engine efficiencies together with the comparison of engine control will be shown.

KEYWORDS

SI engine, HCCI engine, methane, experimental engine testing

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INTRODUCTION

New combustion processes are constantly being developed to reduce air pollution and to achieve legal limits for permissible values of pollutant emissions from internal combustion engines (ICE). Homogeneous Charge Compression Ignition (HCCI) engine is imposed as a potential solution. Combustion process in HCCI engine is a form of Low-Temperature Combustion (LTC) [1]. HCCI engine has the advantages of lower emissions of nitrogen oxides (NO_x) and at the same time high efficiency. Major disadvantage of the HCCI engine is control of the start of the combustion. This combustion start is highly sensitive to intake air temperature [2] causing the start of the combustion to be relatively difficult to control.

Peucheret et al. [3] in their study conducted experimental testing on HCCI engine fuelled with natural gas. Beside higher compression ratio ($\text{CR} = 14.5$) in order to achieve combustion in HCCI engine they had to heat intake air in the range of 140°C to 230°C .

HCCI engine fuelled by biogas tested Bedoya et al. [4,5]. They experimentally demonstrated that HCCI mode of operation has stable combustion with inlet pressure in a range of around 2 bar and intake air temperature above 200°C for equivalence ratios between 0.25 and 0.40 (λ from 2.5 to 4). In their study, as engine fuel, they used biogas as mixture of methane (CH_4) and carbon dioxide (CO_2) in volumetric ratio of 60% CH_4 and 40% of CO_2 .

Kozarac et al. [6] conducted a numerical study of the influence of the exhaust gas recirculation by using negative valve overlap in order to reduce the intake air temperature.

Effect of the compression ratio on HCCI combustion fuelled with methane was studied by Aceves et al. [7]. They used chemical kinetics code to simulate HCCI combustion of methane and air mixtures at compression ratios of 14:1, 16:1 and 18:1 at 1200 rpm. They determined the range of operational conditions where they achieved indicated efficiency above 50% with level of NO_x under 100 ppm.

Although there are studies of combustion process in the HCCI engine fuelled with methane and natural gas there is no real comparison of the combustion process in HCCI mode with combustion process in the SI mode. This study presents comparison of these two types of processes in IC engine.

In this study engine is fuelled with methane which is characterised as a gas with high auto ignition temperature. After reviewing the literature it is concluded that in order to achieve stable HCCI combustion it is necessary to have higher compression ratio than in SI engine and in this study the compression ratio of 18:1 was used. Furthermore, in addition to necessary increase of the compression ratio it is also necessary to heat intake charge in order to achieve stable combustion in HCCI engine.

EXPERIMENTAL SETUP

In the Laboratory for IC Engines and Motor Vehicles of the Faculty of Mechanical Engineering and Naval Architecture an experimental setup for internal combustion engine testing is developed. Core of the setup is a single cylinder diesel engine Hatz 1D81Z (Table 1.) that is modified so it can operate in SI and in HCCI mode. Scheme of the experimental setup with all of its significant parts is presented in the Figure 1. In this study engine is fuelled, with methane from gas tank with specification described in Table 2. Port fuel injector HANA H2001 was used for fuel delivery and it is positioned on the engine intake manifold.

Table 1. Engine specification

Data	Value
Number of cylinders	1
Bore (mm)	100
Stroke (mm)	85
Connecting rod length (mm)	127
Intake valve open IVO ($^{\circ}$ BTDC)	20
Intake valve close IVC ($^{\circ}$ ABDC)	50
Exhaust valve open EVO ($^{\circ}$ BBDC)	26
Exhaust valve close EVC ($^{\circ}$ ATDC)	20
Compression ratio (-)	18

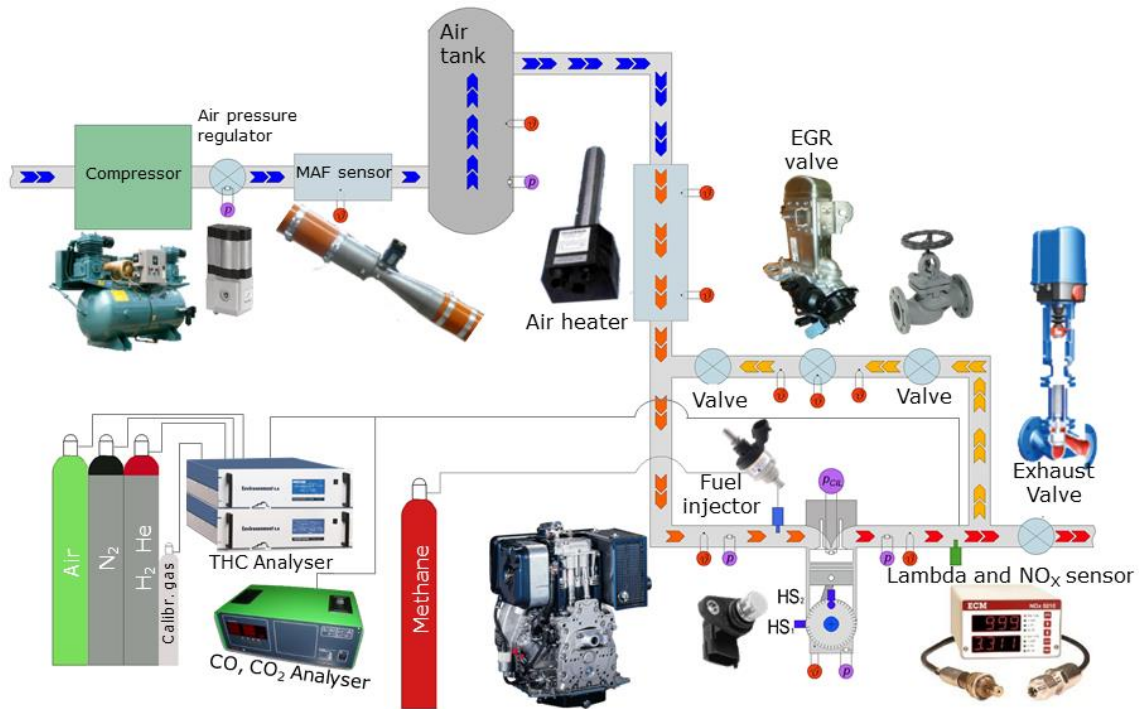


Figure 1. Scheme of the experimental setup

Table 2. Specification of the fuel

Component	Value
CH ₄	99.5 vol %
O ₂	≤ 100 ppm vol.
N ₂	≤ 600 ppm vol.
H ₂	≤ 2000 ppm vol.
Molar mass	16.04 g·mol ⁻¹
Density	0.656 g/L (gas, 25 °C, 1.01325 bars)
Lower heating value (LHV)	50 MJ/kg
Auto ignition temperature	580 °C

In-cylinder pressure is measured with AVL GH14DK sensor which is synchronised with pressure sensor AVL LP11DA installed into the manifold. In order to achieve adequate conditions for ignition of the air to fuel mixture and to control combustion phasing Osram

Sylvania air heater with 18 kW of installed power was used to heat the intake air. For emissions measurement, equipment listed in Table 3 is used.

Table 3. Emissions measurement equipment

Component	Device	Range
NO _x	ECM NO _x 5210t Analyzer	0-5000 ppm
THC	Environnement Graphite 52M	0-10000 ppm
CO	Bosch ETT 8.55 EU	0 – 10 %
CO ₂	Bosch ETT 8.55 EU	0 – 18 %

Emissions of carbon monoxide (CO) and carbon dioxide (CO₂) are measured by the nondispersive infrared (NDIR) method, hydrocarbon (HC) is measured by flame ionisation detector (FID), and NO_x measurement with ceramic NO_x sensor. Intake air flow is measured with laminar mass flow meter TSI 2017L.



Figure 2. Photography of the experimental setup

EXPERIMENTAL TESTING

This study presents testing of the engine operated in SI mode with λ equals to 1 (hereinafter referred to as SI-1) and λ equals to 1.2 (hereinafter referred to as SI-2). Also engine is tested in HCCI mode of operation. This research presents comparisons of the operating points in different mode of engine operation at three different levels of IMEP labelled as IMEP 1, IMEP 2 and IMEP 3. The difference between IMEP of SI-1, SI-2 and HCCI mode at the same speed and IMEP level is presented in Figure 3.

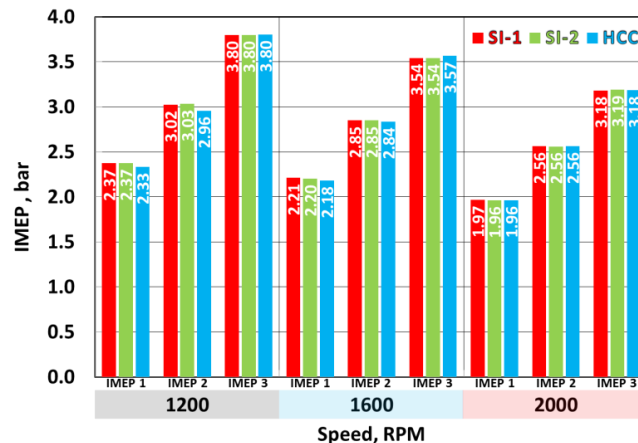


Figure 3. IMEP levels for SI (red and green columns) and HCCI mode (blue columns)

Figure 3. presents IMEP value for nine operating points in SI-1 (red column), nine in SI-2 (green column) mode and nine operating points in HCCI (blue column) mode of operation. Three level of IMEP at engine speed 1200 rpm, three levels at 1600 rpm and three level of IMEP at engine speed of 2000 rpm. For the same engine speed level of IMEP is compared for all three modes of operation.

Furthermore, this research presents a comparison of in-cylinder pressure, temperature and rate of heat released (ROHR) obtained by SI-1, SI-2 and HCCI mode of operation at three different engine speeds (1200, 1600 and 2000 rpm). The emission levels of the HC, CO, CO₂ and NO_x are also compared for all engine modes of operation.

Control mechanism for the start of the combustion in SI and in HCCI mode of operation is different. In SI mode of operation combustion is controlled by spark plug where combustion phasing is determined by spark timing (Figure 4. left).

In the case of HCCI mode the combustion start and combustion phasing is determined by intake air temperature which is controlled by the installed air heater (Figure 4. right). By increasing intake air temperature combustion phasing was advanced.

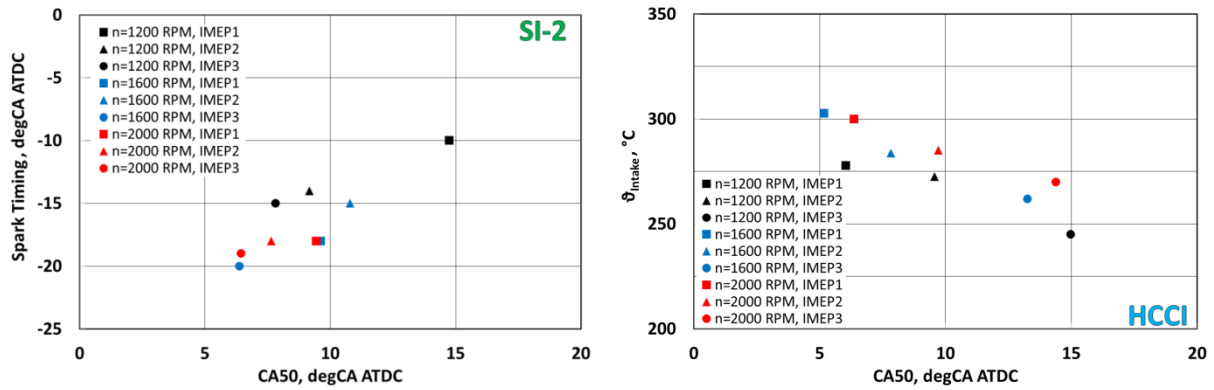


Figure 4. Combustion phase control in SI-2 (left) and in HCCI (right) mode of operation

Engine load in SI-1 and SI-2 mode of operation is controlled with a throttle by changing intake manifold pressure (Figure 5. left) at the stoichiometric air to fuel mixture for SI-1 and at $\lambda = 1.2$ for SI-2.

In HCCI mode of operation, engine load is controlled by changing air to fuel mixture. To obtain higher engine load mixture is richer, λ is equal 2.5 for lowest load, 2.1 for partial load and 1.9 for highest engine load obtained in this study.

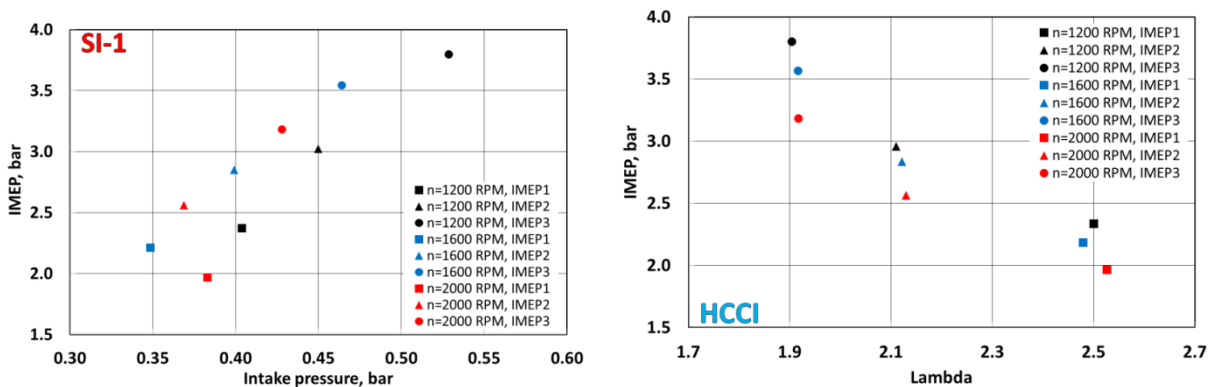


Figure 5. Control method of the engine load in SI-1 (left) and in HCCI (right) mode of operation

Each displayed operating point in SI and HCCI mode of operation is optimised in such a way that chosen combustion phase (CA50) is such that criteria for ringing intensity, detonation and coefficient of variation of IMEP are fulfilled.

RESULTS AND DISCUSSION

Engine testing in SI mode of operation is conducted for two different fuel mixtures, SI-1 with a $\lambda = 1$, and SI-2 with $\lambda = 1.2$. SI-1 and SI-2 consists of nine different operating points where each consists of 300 continuous cycles. In both cases variables for engine testing were engine speed, intake air pressure and spark timing.

Engine testing in HCCI mode also included nine different operating points where each point consists of 300 continuous cycles. Variables for HCCI engine testing were engine speed, intake air temperature and air to fuel ratio.

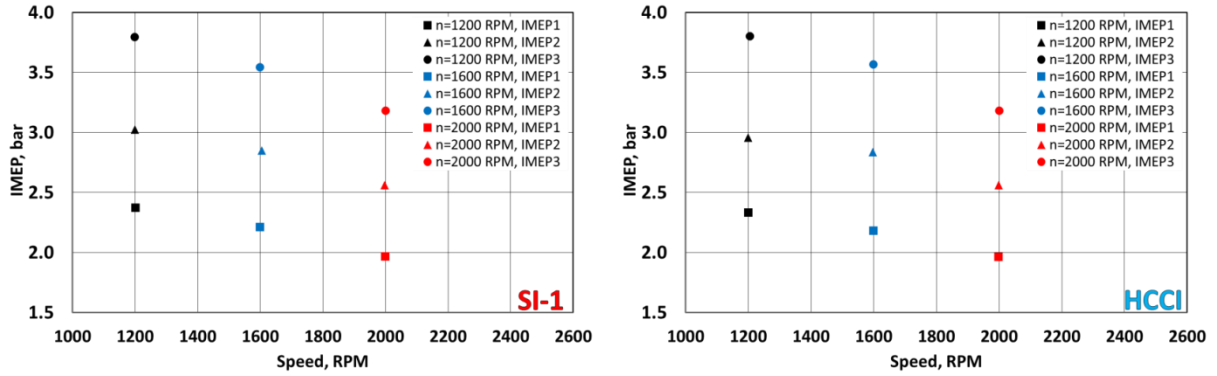


Figure 6. Operating points in SI-1 (left) and HCCI (right) mode of operation

Combustion instability of the IC engine is characterized by the coefficient of variation of the indicated mean effective pressure of the engine, CoV(IMEP). This coefficient represents standard deviation ($\sigma(\text{IMEP}_n)$) of the IMEP divided by the mean value ($\mu(\text{IMEP}_n)$) of the IMEP over a number (n) of consecutive combustion cycle.

$$\text{CoV(IMEP)} = \frac{\sigma(\text{IMEP}_n)}{\mu(\text{IMEP}_n)} \quad (1)$$

In this study measurement of each operating point consists of 300 continuous cycles, which were then used to calculate CoV(IMEP). Limit for the CoV(IMEP) for SI and HCCI mode is set to 10%.

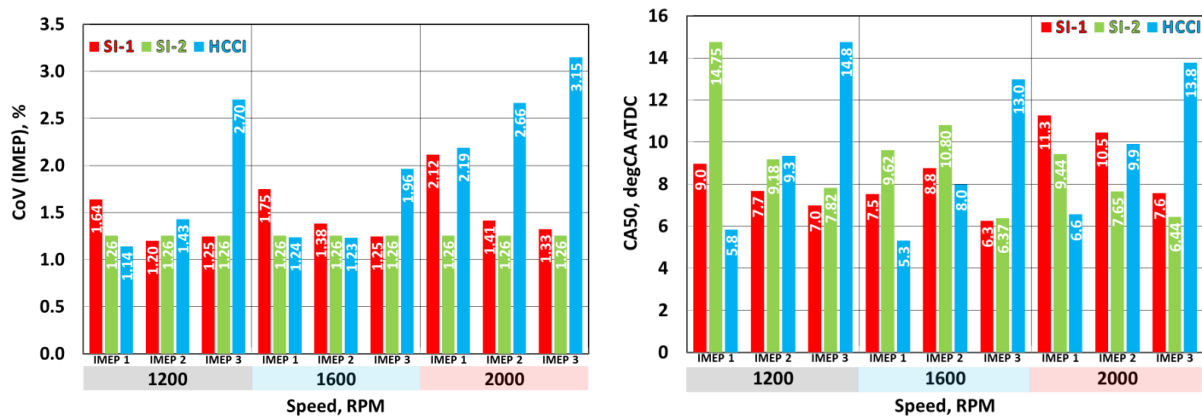


Figure 7. Coefficient of variation of IMEP (left) and combustion phasing (right) for SI (red and green columns) and HCCI mode (blue columns)

Figure 7. left presents coefficient of variation of IMEP for all operating points and it can be concluded that all of the measured operating points had stable combustion.

One of the criteria for optimal combustion phasing is ringing intensity (RI) which is used as a measure of the knock occurrence and it is calculated by the equation published in [8]:

$$RI = \frac{1}{2\gamma} \cdot \frac{\left(\beta \cdot \frac{dp}{dt_{\max}} \right)^2}{p_{\max}} \cdot \sqrt{\gamma R T_{\max}} \quad (2)$$

where β is a scale factor determined from the experimental data (in this case 0.05 factor is used), $(dp/dt)_{\max}$ is the maximum rate of pressure rise, γ is the ratio of specific heats, R is the ideal gas constant, and $T_{\max}$ is maximum in-cylinder temperature.

Limit value for ringing intensity in this research was set to 6 MW/m² [9] and to obtain optimal combustion phasing all of the measured operating points for HCCI mode were below that limit (Figure 8.).

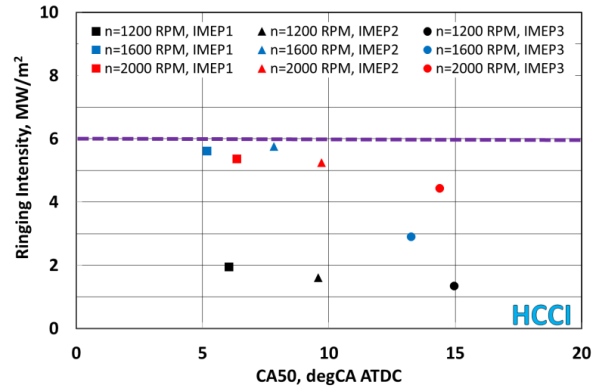


Figure 8. Ringing intensity in HCCI mode of operation

Comparison of the in-cylinder pressure is presented in Figure 9. left. This diagram presents three operating points with the same level of IMEP at same engine speed, red is SI-1, green is SI-2 and blue is in-cylinder pressure in HCCI mode of operation. Since in HCCI mode the load is controlled by λ with intake pressure set to ambient conditions, and in SI mode load is controlled by throttle at $\lambda=1$ or 1.2, much has higher pressure during entire cycle is obtained in HCCI mode.

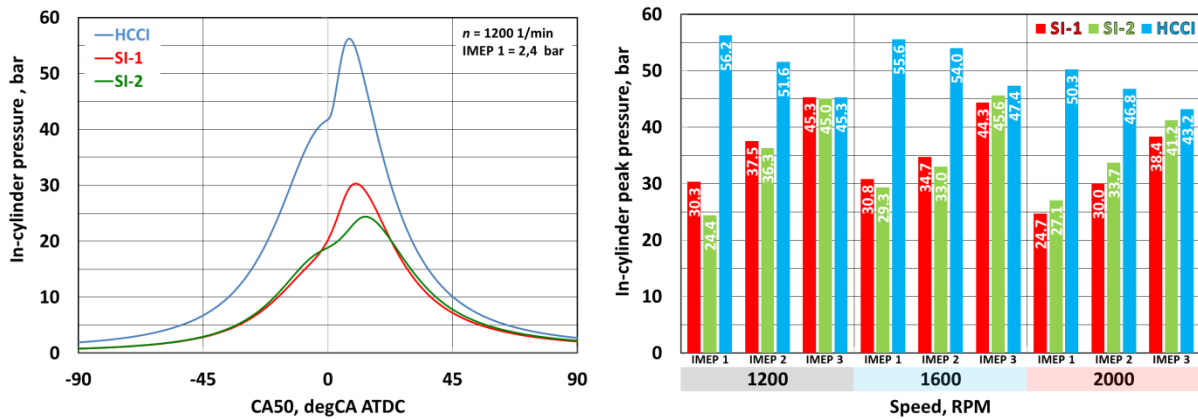


Figure 9. Profile of the in-cylinder pressure (left) and comparison of the in-cylinder peak pressure in SI (SI-1 red line, SI-2 green line) and in HCCI (blue line) mode (right)

As a consequence of higher pressure during entire cycle, the peak pressure is also higher in HCCI mode, and in this study highest in-cylinder peak pressure in HCCI mode was 56 bars while in SI mode was around 45 bars (Figure 9. right). By increasing the level of IMEP at the same speed, in-cylinder peak pressure increases in both SI modes while in HCCI mode of operation it decreases. In this study, HCCI mode has on average 29% higher in-cylinder peak pressure than SI mode. In HCCI mode peak pressure is decreasing as a result of late combustion phasing as presented in Figure 7. left.

Combustion duration is presented in Figure 10. left and presents the difference between start (crank angle where 10% of fuel was burned) and the end of combustion (crank angle where 90% of fuel was burned) displayed in degrees of crank angle. Combustion duration in HCCI mode of operation is lower than 20°CA while in SI mode in some cases the combustion duration is 2 times longer than those in HCCI mode for the same level of IMEP and at the same engine speed.

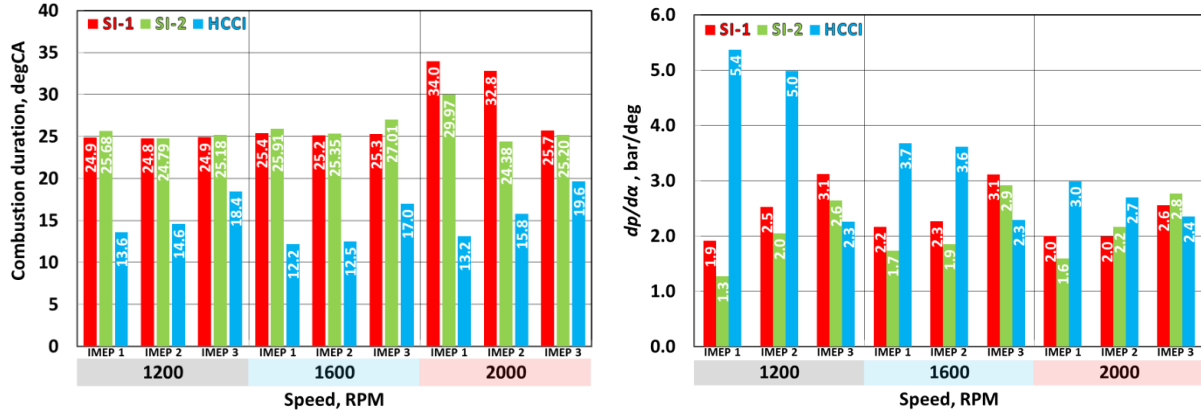


Figure 10. Comparison of the burn duration (left) and pressure rise rate (right) in SI (SI-1 red, SI-2 green) and in HCCI (blue) mode

Pressure rise rate in SI-1 and SI-2 increases as the level of IMEP rises and for the same level of IMEP at different engine speed pressure rise rate is nearly constant. In the HCCI mode pressure rise rate is higher than in the SI mode at lower engine speed. The increase of IMEP and of engine speed decreases the pressure rise rate in HCCI mode because of the late combustion phasing in HCCI mode and therefore at high engine speed the pressure rise rate of HCCI mode is lower than in SI mode. In this study, HCCI mode of operation has in average 33% higher pressure rise rate than SI mode.

Indicated efficiency (Figure 11. left) which is in correlation with the indicated specific fuel consumption (ISFC) (Figure 11. right) is in this study higher in HCCI mode than in SI-1 and SI-2 mode for all measured points. In this study, the average value of indicated efficiency for SI-1 mode is 26%, for SI-2 is 28% and for HCCI mode is 31% which is in average 13% higher than in SI modes. By comparing the indicated specific fuel consumption (ISFC) for SI-1, SI-2 and HCCI mode of operation it can be concluded that for the same level of IMEP at same engine speed HCCI mode has lower ISFC than SI-1 and SI-2 mode. This confirms the fact that the HCCI engine needs less fuel to obtain the same level of IMEP as SI engine. That results as the main advantage of HCCI engine over the SI engine.

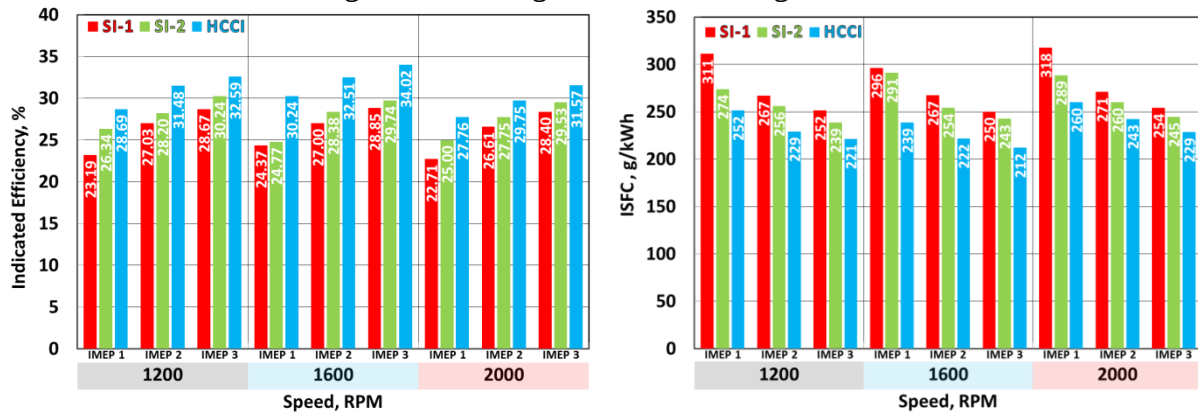


Figure 11. Comparison of the indicated efficiency (left) and indicated specific fuel consumption for SI-1, SI-2 and HCCI mode of operation

In internal combustion engine, the main participant in NO_x is nitric oxide (NO) and nitrogen dioxide (NO_2). Significant formation of the NO_x in the engine cylinder starts at temperatures higher than 1800 K [10].

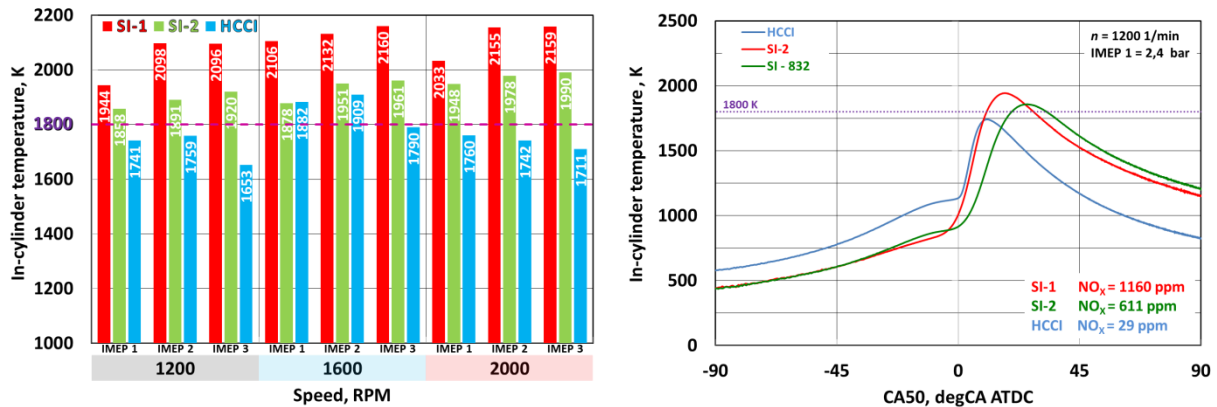


Figure 12. In-cylinder temperature comparison (left) and profile of the in-cylinder temperature as a function of the crank angle (right)

Figure 12. on the right presents comparison of the profiles of the average in-cylinder temperature as a function of crank angle for SI and HCCI mode of operation. It can be observed that average in-cylinder temperature in both SI-1 and SI-2 is higher than 1800 K which results in emissions of NO_x for SI-1 of 1160 ppm and for SI-2 of 611 ppm. Opposite to SI, in HCCI mode the maximum average in-cylinder temperature is below 1800 K (1741 K), and with almost no emission of NO_x (29 ppm measured).

Figure 13. left presents NO_x emissions of all cases and all the values of the emissions are displayed in g/kWh (grams per kilowatt and hour) so that it can be easier to compare the emission of two different combustion processes in the engine cylinder and to compare that with emission limits.

Emissions of the NO_x in both SI modes are much higher than in HCCI mode in all of the measured cases as it is presented in Figure 13. Reason for that is highest in-cylinder temperature over 1800 K in both SI modes of operation and in all operating points as presented in Figure 12. Furthermore, by increasing the engine load i.e. IMEP in SI mode level of NO_x also increases.

In this study, HCCI mode of operation has in average 25 times lower NO_x emissions than SI-1 and SI-2 mode of operation. Also one has to notice that in HCCI model the NO_x emissions are close to the limiting values for heavy duty engines (in some cases lower and in some slightly higher than limit) while in SI mode the values are much higher.

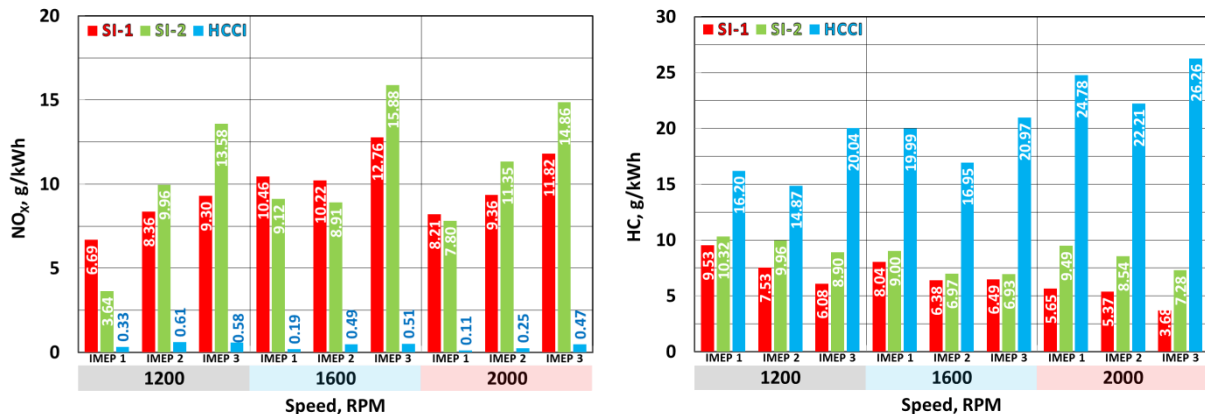


Figure 13. Emissions of NO_x (left) and HC (right) displayed in g/kWh

Emissions of hydrocarbons (HC) for all operating points are presented in Figure 13 right. As the mixture is leaner emission of the hydrocarbons is higher, and therefore HCCI mode of operation because it works with very lean mixtures (λ up to 2.5 in this study) has in some cases 3 times higher emission of HC. HC emissions of SI mode are between 6 and 11 g/kWh, and this value is slightly decreasing as the engine speed and load increase. Opposite to SI operation, emission of HC in HCCI mode increases when the engine speed, and in some cases the engine load, increases. Emission of HC is more than two times higher in some of the HCCI cases compared to corresponding SI modes. It has to be noticed that all operating points (SI and HCCI mode) are significantly above limits for HC emissions of heavy duty engines and would require aftertreatment.

The emission of carbon monoxide (CO) decreases with the increase of the engine load in all of the operating points. When engine operates in SI mode with lean mixture ($\lambda = 1.2$), mode SI-2, emissions of CO are under 5 g/kWh which is lower than in SI-1 and HCCI mode of operation. Although literature shows that CO emissions of HCCI combustion are higher than conventional modes of combustion one can notice that HCCI mode in this works shows lower CO emission than SI with $\lambda = 1$. In all operating points emissions of CO₂ in HCCI mode are lower than in the SI mode as shown in Figure 14 right.

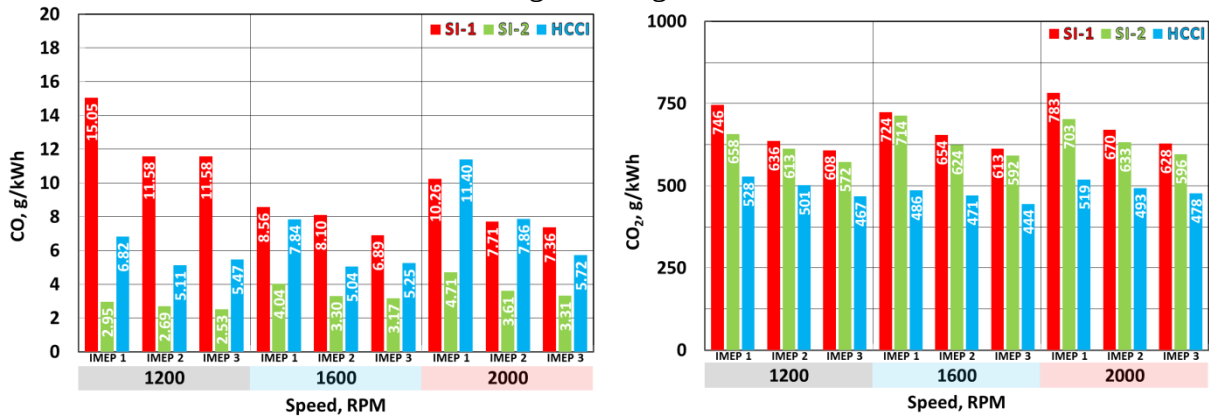


Figure 14. Emissions of CO (left) and CO₂ (right) displayed in g/kWh

Comparison of the rate of heat release (ROHR) for case IMEP 1 at 1200 rpm for SI and HCCI mode is presented in Figure 15 left. In HCCI mode maximum value of ROHR is 57.3 J/°CA at 5.9 °CA ATDC, for SI-1 mode is 34.6 is J/°CA at 8.8 °CA ATDC and for SI-2 mode is 26.9 is J/°CA at 14.8 °CA ATDC. It can be observed that for the same level of IMEP at same engine speed combustion phasing is closer to the TDC and at the same time peak value of the ROHR is almost 2 times higher than in SI-1 and SI-2 mode which is result of shorter combustion duration in HCCI mode.

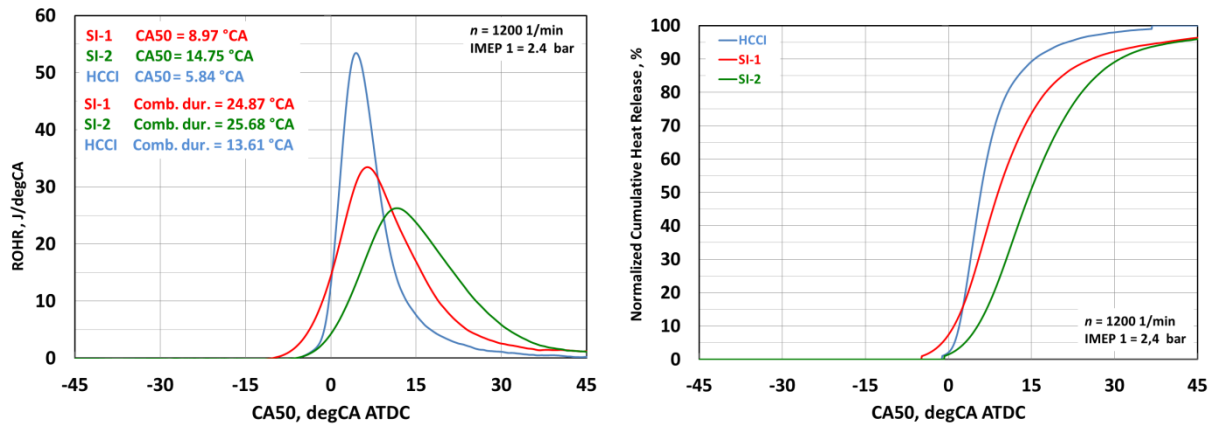


Figure 15. Comparison of the ROHR (left) and normalized cumulative HR for SI-1 (red line), SI-2 (green line) and HCCI (blue line) mode for case IMEP 1 at 1200 rpm

HCCI mode has earlier combustion phasing, CA50, for the same engine load at the same engine speed. Figure 15. right presents normalized cumulative heat released in all three modes. One can notice that combustion process in HCCI engine starts later then in SI-1 mode but it is much faster and it can be approximate to the ideal Otto cycle (combustion at constant volume).

CONCLUSION

This study presents a comparison of the two types of the combustion processes in IC engine, SI and HCCI process. SI mode of operation is performed with two cases of air to fuel mixtures ($\lambda = 1$ and $\lambda = 1.2$). The research showed that the HCCI mode compared to the SI mode has:

- Two times shorter combustion duration in some cases.
- On average 30% higher in-cylinder peak pressure.
- On average 33% higher pressure rise rate.
- On average 13% higher indicated efficiency.
- In most cases lower emissions of carbon monoxide than in SI mode with $\lambda = 1$.
- Higher emissions of carbon monoxide than in SI mode with $\lambda = 1.2$.
- Lower emissions of carbon dioxide.
- On average 25 times lower NO_x emissions.
- On average 63% higher emissions of hydrocarbons.

In addition to the higher compression ratio, intake charge must be heated in order to achieve the ignition of the air to fuel mixture in the engine cylinder. Since the start of the combustion is very sensitive to the intake air temperature, further work on combustion control in the HCCI engine is required and it is considered very interesting primarily due to the positive characteristics in terms of emissions, especially the emissions of nitrogen oxides.

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NOMENCLATURE

ABDC	After Bottom Death Centre	IMEP	Indicated Mean Effective Pressures
ATDC	After Top Death Centre	ISFC	Indicated Specific Fuel Consumption
BBDC	Before Bottom Death Centre	LTC	Low Temperature Combustion
BTDC	Before Top Death Centre	NDIR	Nondispersive Infrared
CA	Crank Angle	NO	Nitric Oxide
CH ₄	Methane	NO ₂	Nitrogen Dioxide
CO	Carbon Monoxide	NO _x	Nitrogen Oxides
CO ₂	Carbon Dioxide	PM	Particulate Matter
CoV	Coefficient of Variation	PPM	Parts per Million
CR	Compression Ratio	PRR	Pressure Rise Rate
FID	Flame Ionisation Detector	RI	Ringling Intensity
HC	Hydrocarbon	ROHR	Rate of Heat Release
HCCI	Homogeneous Charge Compression Ignition	SI	Spark Ignition
ICE	Internal Combustion Engine		

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