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# HCCI Combustion Phasing in a Multi Cylinder engine using Variable Compression Ratio

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## ABSTRACT

Combustion phasing in a Homogeneous Charge Compression Ignition (HCCI) engine can be achieved by affecting the time history of pressure and temperature in the cylinder. The most common way has been to control the inlet air temperature and thereby the temperature in the cylinder at the end of the compression stroke. However this is a slow parameter to control, especially cycle to cycle. A multi cylinder engine using Variable Compression Ratio (VCR) for controlling the compression temperature and consequently the combustion phasing is used in the experiments. Operating range in terms of speed and load is investigated in naturally aspirated mode. Trade-off between inlet air temperature and Compression Ratio (CR) is evaluated. Primary reference fuels, isooctane / n-heptane, are used during the tests. High speed HCCI operation up to 5000 rpm is possible with a fuel corresponding to RON 60. The effect of octane number with and without exhaust cam phasing is also investigated. Brake thermal efficiency of 33% at a maximum load of 4.4 bar BMEP for 2000 rpm is achieved.

## INTRODUCTION

The Homogeneous Charge Compression Ignition (HCCI) engine can be understood as a hybrid between the Spark Ignition (SI) and Compression Ignition (CI) engines. In the SI engine, fuel and air is mixed homogeneously before it enters the cylinder. It is then compressed and ignited by a spark plug at the most convenient time for the combustion process. To control the load of an SI engine, a throttle is used to adjust the amount of mixed air and fuel that enters the cylinder. In the CI engine, air is compressed to a higher pressure than in the SI engine, and fuel is injected at high pressure into the hot compressed air and auto-ignition occurs. By adjusting the amount of injected fuel, the load is controlled and hence no throttling is necessary.

HCCI engines use a premixed air and fuel mixture like the SI engine and compress this mixture to auto-ignition like the CI engine. There are various parameters to take into account in order to obtain HCCI combustion. Temperature and pressure in the cylinder at the end of the compression stroke, auto ignition properties of the fuel, and amount of exhaust gas residuals all affect the HCCI ignition process. The temperature has to be higher at the end of the compression phase, compared to the one in the SI engine, in order to cause auto ignition with conventional SI engine fuels.

The first presented results of HCCI engines were performed on 2-stroke engines [1-2]. The primary purpose of using HCCI combustion in 2-stroke engines is to reduce the HC emissions at part load operation, and to decrease fuel consumption by stabilizing the combustion of lean mixtures. In four-strokes engines auto ignition can be achieved through a high Compression Ratio (CR), pre heating of the inlet air and/or use of retained exhaust gas residuals [3-9]. In two-strokes, residual gas is always present because of incomplete scavenging, and therefore no pre heating is necessary. The objectives of using HCCI in 4-stroke SI engines are to decrease fuel consumption at part load, i.e. reduce pumping losses. The main goals in CI engines are to reduce Nitrogen Oxides (NOx) and particulates.

The low combustion temperature and higher cylinder pressures with HCCI combustion leads to higher HC and CO emissions than from SI and CI engines. The exhaust gas temperature is also a problem for the catalyst, since a fairly high temperature is needed to start the oxidation/reduction. Another drawback is the very high heat release rate, which leads to high maximum pressures and noise levels. To avoid too fast combustion, a diluent must be used. The diluent can be any combination of air, residual gas and Exhaust Gas Recirculation (EGR). In four-strokes, EGR is used both as a diluent to slow down combustion and as bulk to control the temperature of the intake mixture. Since the onset of combustion is dependent on temperature, pressure, and mixture formation in each cylinder, controlling the combustion process is a challenge. One way to monitor the onset of combustion is to measure the cylinder pressure in each cylinder and calculate the heat release online. The Crank Angle of 50% heat release (CA50) then serves as a quantitative measure of the combustion phasing [10].

The objectives of this study are to investigate the trade-off between inlet air temperature and CR, and to find the load/speed range for HCCI operation of a Naturally Aspirated (NA) multi cylinder engine using variable CR. The operating range is examined through operation with primary reference fuels with various Octane Numbers (ON) and by manually phasing the exhaust cam.

## EXPERIMENTAL APPARATUS

The engine used is a five-cylinder 1.6L Saab Variable Compression (SVC) prototype engine. This engine is the base for a downsized highly boosted SI engine concept [11]. The engine VCR mechanism can be seen in Figure 1. The CR in the SI version can be varied between 8 and 14 by tilting the upper part of the engine up to four degrees. To achieve HCCI combustion without excessive inlet air heating or excessive amounts of hot residuals a higher CR than in the original engine is needed. In this experiment the pistons were modified to a CR range between 9 and 17.

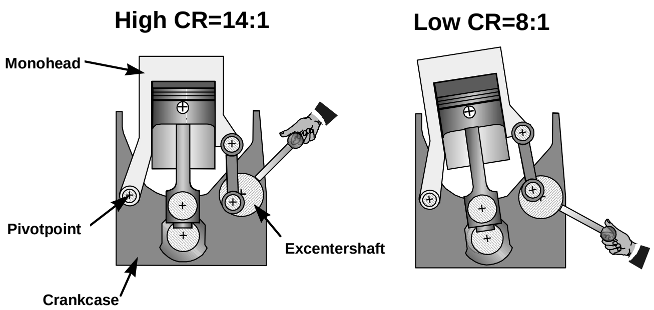


**Figure 1. Saab Variable Compression (SVC) engine [11].**

The exhaust valve timings can be changed in the test engine by cam phasing. The cam phasing is done manually and it can be adjusted between 0 and 50 Crank Angle Degrees (CAD) later than standard timing, to retain more hot residuals.

The engine is run NA during the tests presented in this paper. An electrical inlet air pre-heater of 11 kW is fitted between the air filter and the inlet air manifold. The performance measurements are not corrected for heater power, since this heating power can be recovered from the exhaust gas heat. The geometric specifications of the SVC engine can be seen in Table 1.

Table 1. Geometric specifications of the engine.

| | |
|---|---|
| Displacement | 1598 $cm^3$ (320 $cm^3$/cyl) |
| Number of cylinders | 5 |
| Compression Ratio | Adjustable 9–17:1 |
| Bore x Stroke | 68mm x 88mm |
| Exhaust valve open | 45°BBDC at 0.15mm lift |
| Exhaust valve close | 7°ATDC at 0.15mm lift |
| Inlet valve open | 7°BTDC at 0.15mm lift |
| Inlet valve close | 49°ABDC at 0.15mm lift |
| Combustion chamber | Pent roof |

For monitoring the cylinder pressures the spark plugs are removed from all cylinders and replaced by water-cooled cylinder pressure sensors from Kistler, model 6043A. An A/D-converter, Wavebook 516 with sample and hold from IOtech, capable of 1M samples/s is used to sample the cylinder pressure. The sample rate is 5 samples per CAD per cylinder for engine speeds below 3000 rpm and 2.5 samples per CAD per cylinder above 3000 rpm. The regulated emissions are measured with a Horiba exhaust gas analyzer MEXA-8120-F. The relative air/fuel ratio, lambda is calculated from the exhaust gas emissions. Fuel consumption is measured by weighing.

The standard engine control system is only used for opening the throttle in HCCI operation. The air throttle is kept open through out the tests. A modified and further developed control program originally written by Olsson et al. [10] is used for controlling fuel supply, CR, and inlet air temperature. The inlet air temperature control is actuated through the electrical heater. The control program calculates on-line different variables from the cylinder pressure for control and engine protection, e.g. peak cylinder pressure, maximum pressure rise rate (dP/dCA), net IMEP, CA50, etc. In this study no closed loop control for combustion phasing is used. The CA50 can be controlled through inlet air temperature, CR, and fuel amount. The set points for these parameters can be adjusted manually through the graphical user interface. The amount of fuel to the engine can be controlled cylinder-individually, which provides a means for cylinder-individual phasing of CA50 by adjusting the air/fuel ratio. The injection time requested by the control program is sent via a parallel port to one PIC-processor per injector.

Other variables that are used for control, as inlet air pressure, inlet air temperature, and CR, is logged with a multi function PCI card NI6052E from National Instruments. The sampling rate is one tenth of the sampling rate for the cylinder pressure. The CR is measured and calculated from an angular sensor on the eccentric shaft, see Figure 1. The eccentric shaft is used for tilting the engine cylinder head to achieve different CR. This measured CR is only used for CR control. For post processing heat release analysis the CR is estimated from motored cylinder pressure traces. The heat release is a one-zone model using an adjusted Woschni coefficient for wall heat transfer. Besides the faster measured variables, used for control, are several other variables logged, i.e. temperatures and pressures of air, exhaust, water, and lubricating oil.

## TEST PROCEDURE

The tests can be divided into two parts. In the first part, the trade-off between inlet air temperature and CR is investigated by sweeping lambda at 2000 rpm with three different inlet air temperatures, 50, 75, and 100°C. Lambda, i.e. load, is varied from lean to rich by changing the injected amount of fuel for each temperature. CR is adjusted to achieve Maximum Brake Torque (MBT) timing for CA50 if not restricted by other limits. The MBT timing for CA50 is approximately 5-7 CAD ATDC. There are different limiting factors for CA50 timing for different operating conditions. At higher loads it can be maximum cylinder pressure, maximum dP/dCA or NOx that limits engine operation [13]. The chosen NOx limit in these tests is 15 ppm-dry at actual $O_2$ level and max 10 bar/CAD pressure rise. In that case CA50 is retarded from MBT. At low load misfiring is the limiting factor. A fuel with Octane Number 60 (ON 60) is used for this test. The fuel is mixed from 60% i-octane and 40% n-heptane.

Since the engine is run NA in this test, dilution requirements, air or EGR, is an obstacle against higher load. The engine load is controlled with fuel amount, which decrease lambda at increasing load and hence increase NOx and dP/dCA.

The second part is a test of how ON and exhaust gas residuals, achieved by retarded exhaust cam-phasing, influence the operating range in terms of speed and load. The standard case is ON 60 and standard cam phasing. The engine is tested between 1000 and 5000 rpm. There are some speed related problems with the control system communication to the injection system at some test cases, and thus not all configurations are tested at the top speed 4000-5000 rpm. For the test case with ON 40 only two speeds are tested. The operating limits are defined to max 15 ppm-dry at actual $O_2$ level, max 10 bar/CAD pressure rise, and about 6% COV net IMEP average of all cylinders. The limit for high NOx can be seen in Figure 2, where the operating range for the ON 60 case is presented with lines for constant NOx. The test points are marked as circles. The maximum and minimum load lines are drawn between the test points for maximum and minimum load respectively. CR and inlet air temperature is adjusted to achieve MBT timing whenever not limited by high NOx or high COV IMEP.

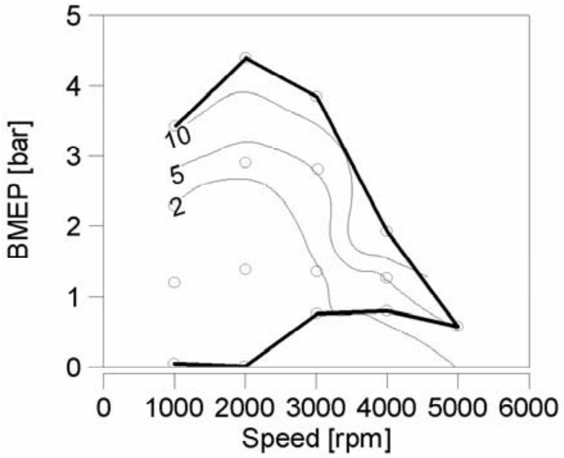


**Figure 2. NOx [ppm] limit for operating range ON 60.**

## RESULTS AND DISCUSSIONS

### TRADE OFF BETWEEN COMPRESSION RATIO AND INLET AIR TEMPERATURE

As mentioned earlier there is a trade-off between CR and inlet air temperature. The auto ignition of the air/fuel mixture is dependent on the time history of temperature and pressure in the cylinder. The same timing for CA50 can be achieved with different combinations of inlet air temperature and CR. When increasing CR inlet air temperature can be decreased and vice versa.

The lambda range for each temperature in this test can be seen in Figure 3. For the 100°C case lambda varies from 4 to 2.6, while the highest lambda for the 50°C case is 3.4. The rich limit, i.e. high load limit in NA mode, is approximately the same for all of the cases and is NOx limited. The difference in maximum load is due to less air mass, and consequently fuel at the same lambda, to the engine with higher inlet air temperatures. With increasing load, hence decreasing lambda, the inlet air temperature is decreased to keep MBT timing. More dilute mixtures, hence lower load, can be run with higher inlet air temperature.

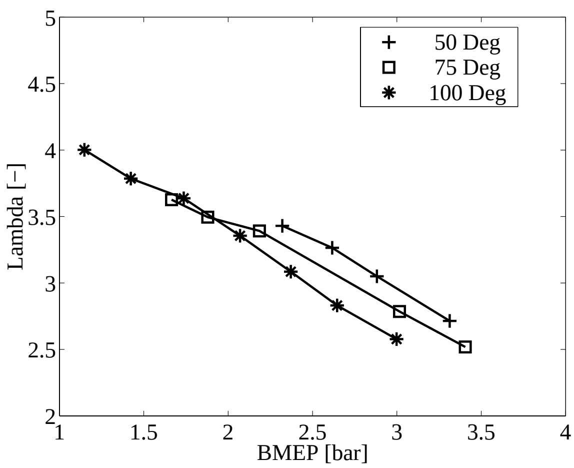


**Figure 3. Possible lambda for three different inlet air temperatures as a function of BMEP at 2000 rpm.**

The CR in the tests is shown in Figure 4. Higher CR is needed with lower inlet air temperature to keep MBT timing and avoid misfiring. In all temperature cases maximum CR is used at minimum load. At maximum load the CR is higher for lower inlet air temperatures and subject to the NOx limit.

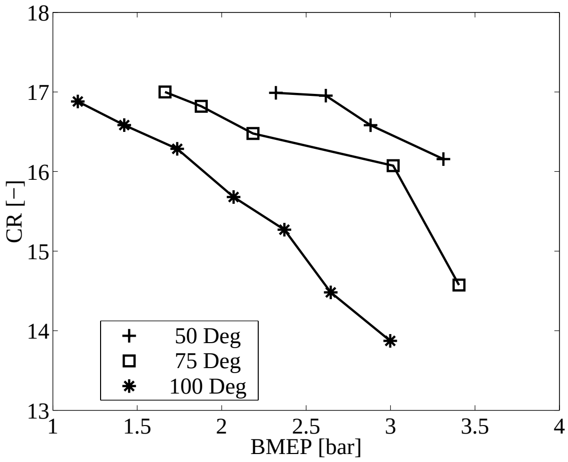


**Figure 4. Used CR for three different inlet air temperatures as a function of BMEP at 2000 rpm.**

In Figure 5 the brake thermal efficiency is shown for various inlet air temperatures. Lower inlet air temperature, hence higher lambda, and higher CR increase efficiency for constant load. The combustion phasing CA50 was approximately the same for all inlet air temperatures and slightly retarded at higher loads, about 5.5°ATDC compared to about 3°ATDC at low loads. This small difference in timing does not affect the results because the efficiency versus timing graph close to MBT timing is almost flat. At lower loads earlier combustion timing also stabilizes combustion to some extent. The efficiency decreases with decreasing load, in spite of higher CR. The main reason is decreasing combustion efficiency, but also the engine mechanical efficiency decreases with decreasing load. In the respect of brake thermal efficiency CR should be kept as high as possible at all loads and combustion timing should be adjusted with inlet air temperature. Any negative influence of too high CR, up to 17:1 for this engine, on the brake thermal efficiency cannot be seen. The lowest BSFC 272 g/kWh, i.e. highest brake thermal efficiency 29.8%, is reached at the highest load, which is 3.3 bar BMEP. A higher efficiency and a higher load are reached in the tests presented in the second part of this paper.

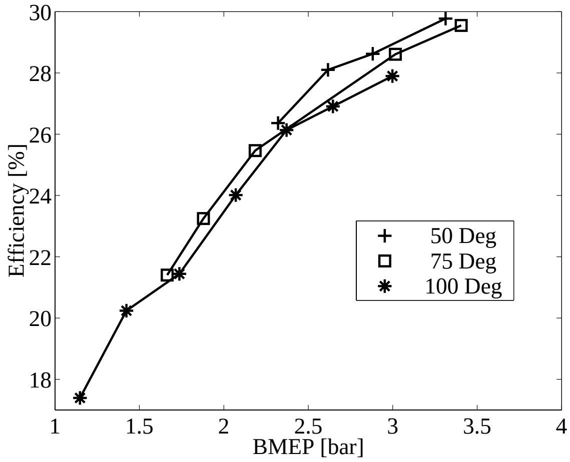


**Figure 5. Brake thermal efficiency for three different inlet air temperatures as a function of BMEP at 2000rpm.**

The combustion efficiency, in Figure 6, decreases rapidly with decreasing load. Higher inlet air temperature, and consequently lower lambda, improves the combustion efficiency for constant load. The leaner combustion with colder inlet air temperature, increases unburned emissions of CO and decreases NOx emissions, see Figure 8-9. The higher CR with lower inlet air temperature affects fuel oxidation. The expansion is faster with higher CR during the rapid burning angle than with lower CR and flame quenching occurs earlier producing more intermediate combustion products, such as CO. This is also found by Christensen et al. [12]. The gain in thermal efficiency, with higher CR, is lost by worse combustion efficiency.

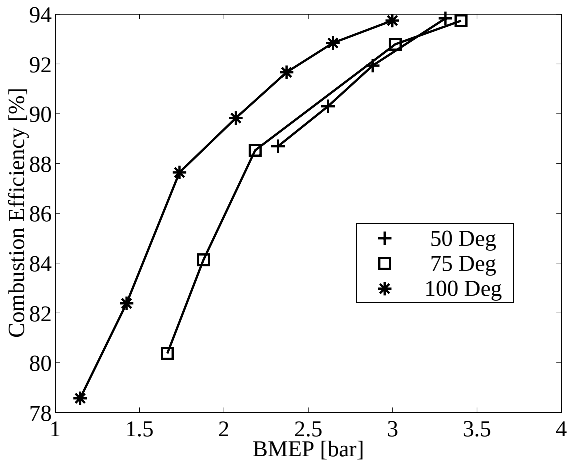


**Figure 6. Combustion efficiency for three different inlet air temperatures as a function of BMEP at 2000rpm**

Engine out emissions are presented from Figure 7 to Figure 9. There is only a minor effect of inlet air temperature on HC emissions at constant load, see Figure 7. This confirms that the fuel oxidation starts in the cylinder but the fuel oxidation is quenched during expansion and produces CO emissions. Figure 8 shows how CO emissions are dependent on inlet air temperature and CR.

Decreasing CR and increasing inlet air temperature for constant load decreases CO emissions. Decreasing load, hence increasing lambda and increasing CR, increases CO emissions. The lowest load and highest CO emissions, i.e. lowest combustion efficiency, was however only reached with 100°C inlet air temperature. To reach lower load with 75 and 50°C inlet air temperature a higher CR would have been needed than 17:1. The limiting factor for lower load was misfiring in some cylinders, and this is dependent on cylinder balancing. At the highest loads for the different inlet air temperatures the decreasing CO emission trend levels out. In this region other mechanisms than quenching of bulk fuel oxidation affects the CO production, i.e. wall and crevice effects.

Engine out NOx emissions are presented in Figure 9. NOx formation is mainly dependent on combustion temperature, which is directly connected to lambda, i.e. mixture dilution, and inlet air temperature. Higher inlet air temperature leads to less air mass, which leads to richer mixtures for the same load. At low loads close to misfire limit the NOx decrease levels out. The probable reason is that the measurement range for the exhaust gas analyzer is reached.

If the results from this engine are compared to earlier tests made by Christensen et al. [9], with a single cylinder 1.6L truck engine, the same CR and inlet air temperatures in this test require fuel with higher ON. For example Christensen et al. ran commercial gasoline (RON 98) with CR 17:1 and inlet air temperature 120°C. The main difference between the engines is because of smaller cylinder volume and larger heat losses in the combustion chamber in the Saab SVC test engine, which is optimized for high load SI operation. The difference in combustion chamber volume to combustion chamber area ratio is an indication of heat losses. It is 1.9 mm compared to 3.2 mm in the truck engine. When comparing exhaust gas emissions, at the same lambda and almost the same ON, HC is about 4 g/kWh higher, CO and NOx are about two times higher than in the truck engine. A higher inlet air temperature and higher CR is needed in the smaller engine with the same fuel ON.

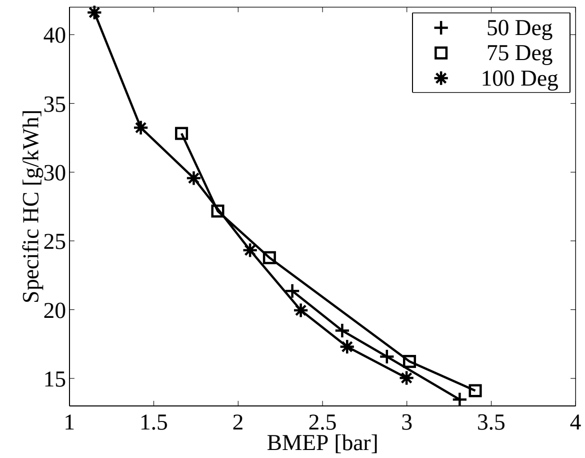


**Figure 7. Specific HC emissions for three different inlet air temperatures as a function of BMEP at 2000rpm.**

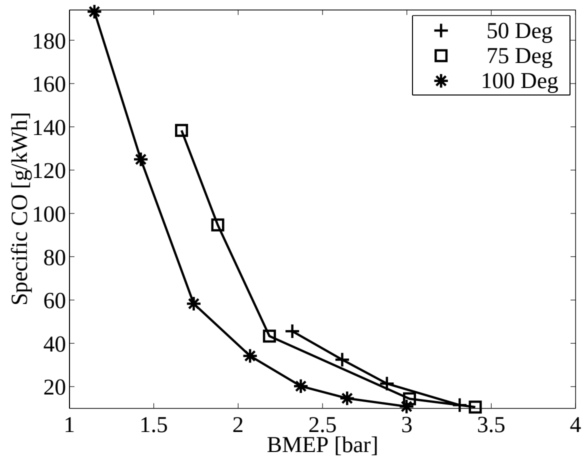


**Figure 8. Specific CO emissions for three different inlet air temperatures as a function of BMEP at 2000rpm.**

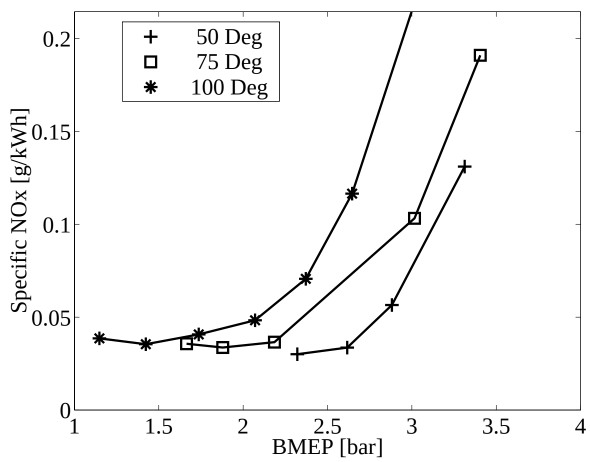


**Figure 9. Specific NOx emissions for three different inlet air temperatures as a function of BMEP at 2000rpm.**

The best combination of CR and inlet air temperature for a specific load depends on the variable to be optimized. For highest brake thermal efficiency and lowest engine out NOx emissions, a high CR is beneficial, but for CO emissions, higher inlet air temperature is better. CO emissions can however be easily reduced with an oxidation catalyst, so keeping the CR as high as possible is the preferred for this engine. To reach low load, both high CR and high inlet air temperature are necessary. To further decrease load, even higher CR than 17:1 would be needed, unless other measures such as exhaust gas residuals or fuel with lower ON are available. This is discussed in the second part of the paper, which now follows

## EXHAUST CAM PHASING AND OCTANE NUMBER

In Figure 10 to Figure 13 the speed/load operating ranges are shown as maximum and minimum load for four cases. The cases are ON 60 with and without exhaust cam phasing, ON 40 without exhaust cam phasing, and ON 80 with exhaust cam phasing. For reference a speed/load range achieved by retaining exhaust gas residuals at low CR [14], often called Controlled Auto-Ignition (CAI), is shown in Figure 14. This was achieved with Variable Cam Timing (VCT) and special camshafts. Note that the fuel in this test had ON 95 and the CR was 10.3:1.

A standard case is chosen with ON 60 and standard valve timing. ON 60 is used to limit the inlet air heat power needed to initiate combustion. A higher CR should allow higher ON to be used or lower inlet air temperature. ON 80 was only tested with retarded exhaust cam with more exhaust gas residuals. Some test points with ON 40 and standard valve timing was tested to see the effect of ON for this particular engine. Exhaust gas residuals were expected to increase the load range for HCCI operation.

### Influence of cam phasing with Octane Number 60

The standard case with ON 60 and no exhaust cam phasing in Figure 10 is operational over the entire speed range up to 5000 rpm. The ON 60 case with retarded exhaust cam phasing in Figure 11 did not reach full speed. There is not much difference in load and speed range between the exhaust cam timings. The limiting factor for higher load, as for all tested cases, is the lack of dilution, i.e. in this case air. At low engine speeds the inlet air temperature has to be kept as low as possible to increase the air mass to the cylinder and to maximize load. However above 2000 rpm the temperature has to be increased to keep combustion phasing and combustion stability within acceptable ranges, but with the drawback of reducing maximum load, see Figure 10.

The inlet air temperature at maximum load is presented in Figure 15. The limiting factor to achieve higher speed is the time available for initiating combustion. Gas exchange was also the high-load limit for the CAI tests made by Ma et al. [14]. Their load and speed range is shown in Figure 14. The operational range with HCCI combustion achieved by VCR is larger than the corresponding one achieved by CAI.

Maximum load is about the same for both ON 60 cases between 2000 and 3000 rpm, but the maximum load decrease faster as speed increases for the phased case. In the standard case combustion timing is retarded from MBT timing to keep NOx below 15 ppm at all the maximum load points, as could be seen in Figure 2. Max dP/dCA is 8 bar/CAD at the highest load points between 1000 and 3000 rpm, and lower at higher speeds. In the phased case however, the CA50 timing is retarded due to NOx between 1000 and 2000 rpm, and due to dP/dCA at higher speeds. The limit value is 10 bar/CAD. CA50 is about 2-3 CAD earlier and maximum cylinder pressures are about 5-7 bar higher in the phased case. The charge heating effect [15] from the hot residuals is the reason for the faster combustion in the phased case. Despite this, NOx decreases with increasing speed for the phased case, and at the same time CO increases. CO emissions are higher and HC emissions are lower in the phased case. In the phased case the CR is lower due to the charge heating effect of hot retained exhaust gas residuals helping to initiate combustion. In the trade-off test between CR and inlet air temperature presented in the first part of this paper, higher CR increased CO emissions due to faster expansion. For the phased case, CR is lower than for the standard case but CO emissions are higher. The increased CO levels are due to incomplete oxidation, i.e. partial burning, and this also increases combustion instability. In the phased case 5000 rpm could not be reached because of combustion instability.

Idle is possible to achieve up to 2000 rpm for both the standard valve timing and for the exhaust cam retard case with ON 60 in contradiction to CAI. At 3000 and 4000 rpm the minimum load is higher for the standard than for the phased case, but 5000 rpm could not be reached at all with the phased exhaust camshaft. Combustion instability and misfiring limit the minimum load. HC emissions are lower and CO emissions are higher for the phased case. COV IMEP is about the same for both cases, but initiating the combustion is easier at low load with the phased case, due to more hot residuals. The need for inlet air heating decreases, however, with more residuals in the cylinder at low load.

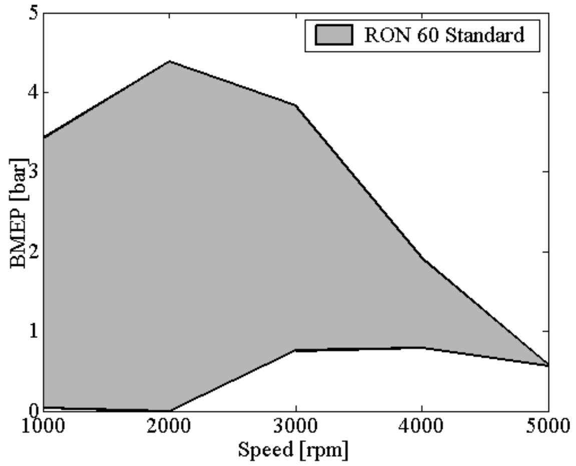


**Figure 10. Load range for the standard case.**

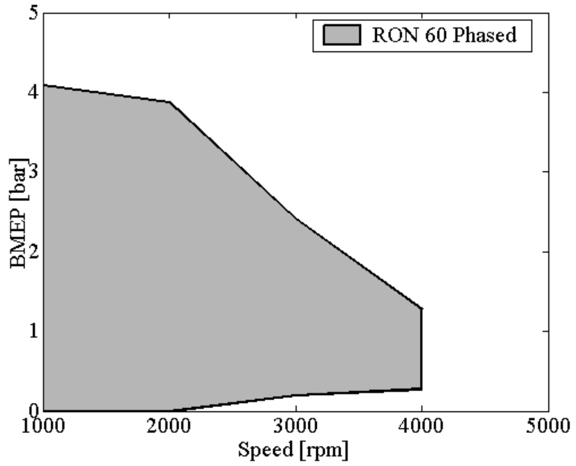


**Figure 11. Load range for ON 60 with retarded exhaust cam between 1000 and 4000 rpm.**

<u>Influence of Octane Number</u>

Lower ON is expected to increase the load range, because the auto-ignition temperature is lower [12], hence lower CR and less inlet air heating is needed. In Figure 12 the ON 40 load range is presented between 2000 and 3000 rpm, and with standard valve timings. Please note that the engine is only tested at these speeds. The ON 40 case should therefore be compared to the standard case of ON 60 without cam phasing. In Figure 13 ON 80 is presented, but with exhaust cam phasing as in the ON 60 phased case.

The influence of ON is clearly seen in Figure 10 and Figure 12. The maximum load at 3000 rpm is slightly higher for ON 40 than the same test point in the standard case, and idle is possible with less inlet air heating than in the standard case, see Figure 16. HC emissions are lower and CO emissions are higher for the ON 40 case. Lower ON with lower auto-ignition temperature is easier to ignite at low load, but the difference is smaller at high load. In both cases, ON 40 and 60 at high load, NOx is the limiting factor.

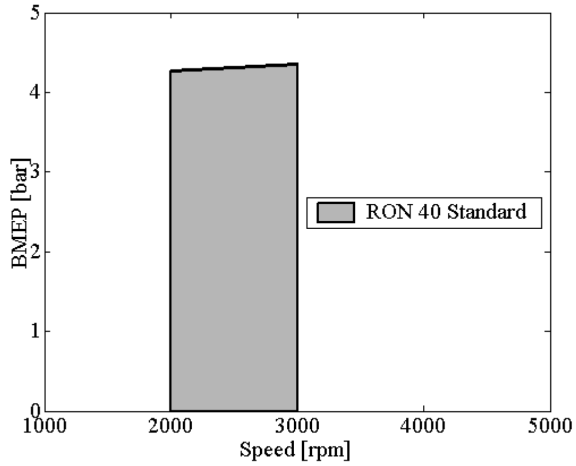


**Figure 12. Tested load range for ON 40 at 2000 and 3000 rpm.**

It was possible to run the engine with higher ON by retarding the exhaust cam, see Figure 13. The load range is smaller compared to ON 60 with phased exhaust camshaft in Figure 11. The same maximum load could not be reached and Idle could not be run at all with ON 80. The limit for higher load is NOx in the whole speed range, compared to high dP/dCA at higher speeds for the ON 60 phased case. Misfiring and high COV IMEP is the limit for lower load. Inlet air temperature shown in, Figure 15 and Figure 16, is higher in the whole speed range for the higher ON. The need for higher mixture temperature with higher ON to initiate the combustion is clear. Some measurement points with commercial gasoline, RON98, were also tested. The test engine could only be run at about 2 bar BMEP and 1000 rpm, with CR 17:1 and 150°C inlet air temperature.

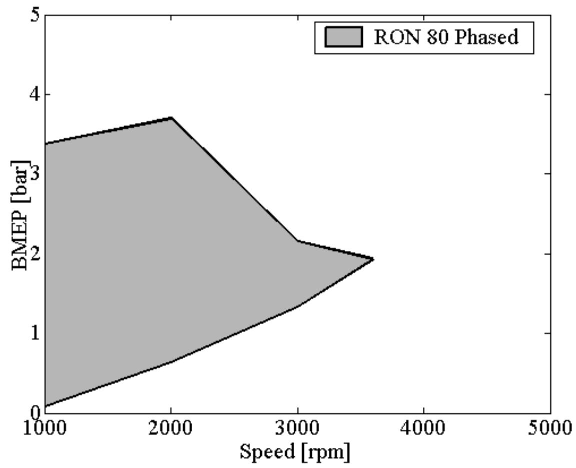


**Figure 13. Load range for ON 80 with retarded exhaust cam.**

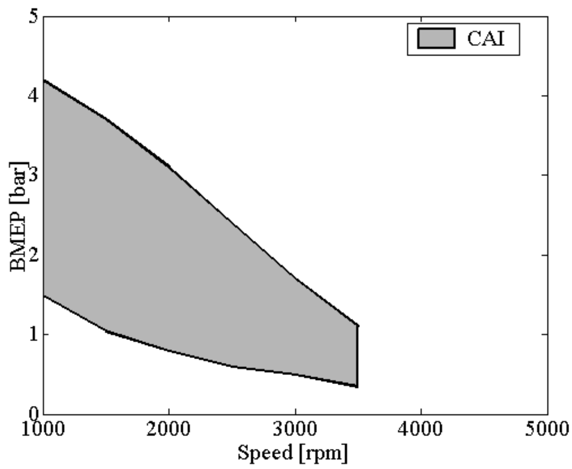


Figure 14. CAI load and speed range[14].

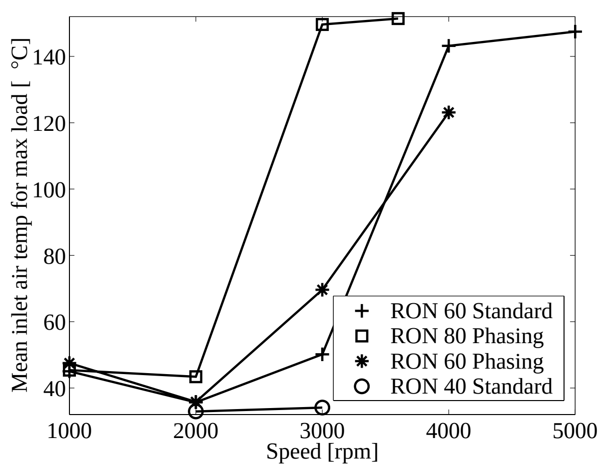


Figure 15. Mean inlet air temperature, measured in the inlet ports, at maximum load.

Inlet air heating

In Figure 15 and Figure 16 the inlet air temperatures for maximum and minimum load are shown respectively over the whole speed range. Inlet air heating is needed to initiate the combustion unless high enough CR or enough exhaust gas residuals are available. At maximum load inlet air temperature is kept as low as possible to maximize the amount of dilution to supress NOx and rate of pressure rise dP/dCA, i.e. noise. As the speed increases and available time for ignition decreases, inlet air temperature is increased to initiate combustion at MBT timing. The drawback of increasing temperature is that the load has to be decreased to avoid too high NOx and dP/dCA, see Figure 10 to Figure 13. At minimum load inlet air temperature is kept high in order to avoid misfiring and also to decrease CO emissions. The inlet air temperature can be replaced by hot residuals to promote ignition at low load, but with the drawback of higher CO emissions. To reduce CO, and improve combustion efficiency, the inlet air temperature should be kept as high as possible at low load and the improvement of auto-ignition with hot residuals should instead be used for decreasing CR.

The highest inlet air temperatures in these tests are chosen with respect to the exhaust gas temperatures in each case. The highest inlet air temperature used is 150°C. The possibility to replace the electric inlet air pre-heater can be estimated from Figure 17, where the applied inlet air temperature and the exhaust gas temperature is shown for both low load and high load for the standard ON 60 case. It is interesting to look at the temperature difference since the mass flow is almost the same in the inlet and the exhaust. The minimum difference is 62°C at 1000 rpm and low load, which would be enough to heat the inlet air with some kind of heat exchanger with an efficiency of at least 62%. This estimation is of course only true for an already running and warm engine.

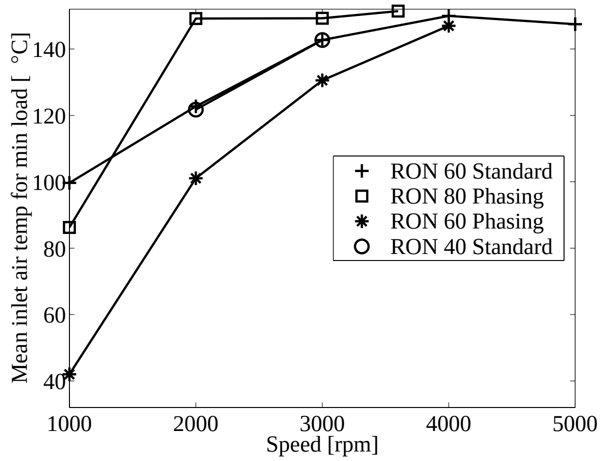


Figure 16. Mean inlet air temperature, measured in the inlet ports, at minimum load.

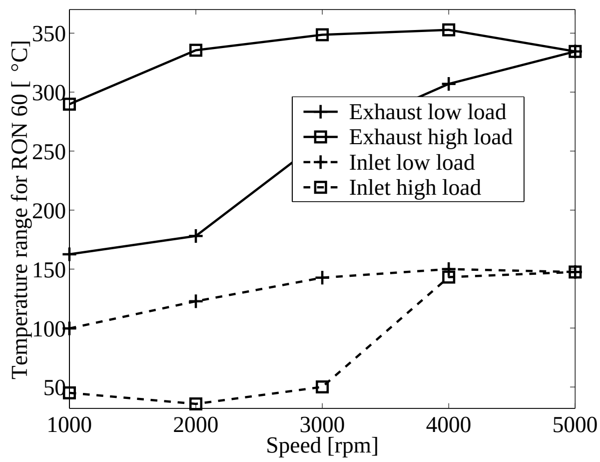


Figure 17. Inlet and exhaust temperatures for the standard case.

Brake thermal efficiency

Iso-lines for brake thermal efficiency over the entire load and speed range for the ON 60 standard valve timing case are shown in Figure 18. The highest efficiency is achieved at the highest load for all the tested speeds, which is explained by the very poor combustion efficiency at low loads. A maximum brake thermal efficiency of 32.8% is reached at 2000 rpm and 4.4 bar BMEP. Gross Indicated efficiency is 44.2%. The brake thermal efficiency is about the same for all tested cases, i.e. different ON and with or without exhaust cam phasing. The efficiency is also almost independent of engine speed.

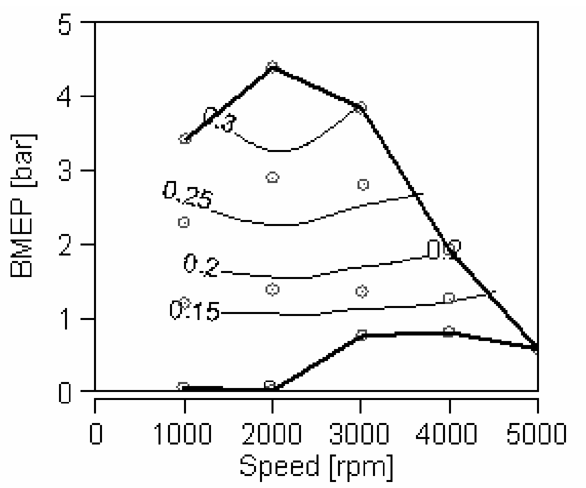


**Figure 18. Brake thermal efficiency for RON 60 standard.**

## CONCLUSION

HCCI combustion has been run with controlled combustion phasing on a multi cylinder engine with VCR and inlet air preheating. Trade off between CR and inlet air temperature has been investigated. Operating range in terms of speed and load has been investigated with and without exhaust cam retard, and with fuels with different ON.

Higher CR can replace inlet air preheating. Brake thermal efficiency increases and NOx emissions decrease, with CR up to 17:1. The drawback of increasing CR is increased CO emission, due to the faster expansion, i.e. shorter reaction time.

Cylinder size has an effect on the need for inlet air heating and CR, due to cylinder wall heat losses. Smaller combustion chamber volume to area ratio increases heat losses, and increases the need for inlet air heating and higher CR.

A load range between idle and 4.4 bar BMEP have been achieved with HCCI combustion. The load is limited by NOx emissions and noise, at high load and misfire at low load.

A speed range between 1000 and 5000 rpm is achieved. The available means for initiating combustion during the available time are limiting higher engine speeds.

Retaining exhaust gas residuals in the cylinder, achieved by exhaust cam phasing, enables easier start and minimum load at increasing speeds. Maximum load is decreased with cam phasing at speeds above 2000 rpm and noise, hence max dP/dCA, increases.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

**ABCD**: After Bottom Dead Center

**ATDC**: After Top Dead Center

**A/D**: Analog / Digital

**BMEP**: Brake Mean Effective Pressure

**BBDC**: Before Bottom Dead Center

**BSFC**: Brake Specific Fuel Consumption

**BTDC**: Before Top Dead Center

**CAD**: Crank Angle Degree

**CAI**: Controlled Auto Ignition

**CA50**: Crank Angle for 50% burned

**CI**: Compression Ignition

**CR**: Compression Ratio

**CO**: Carbon Monoxide

**COV**: Coefficient Of Variation

**dP/dCA**: Maximum Rate of Pressure Rise

**EGR**: Exhaust Gas Recirculation

**HC**: Hydro Carbons

**HCCI**: Homogeneous Charge Compression Ignition

**IMEP**: Indicated Mean Effective Pressure

**MBT**: Maximum Brake Torque

**NA**: Naturally Aspirated

**NOx**: Nitrogen Oxides (NO and $NO_2$)

**ON**: Octane Number

**PCI**: Peripheral Component Interconnect local bus

**RON**: Research Octane Number

**SI**: Spark Ignition

**SVC**: Saab Variable Compression

**VCR**: Variable Compression Ratio

**VCT**: Variable Cam Timing