

High Load HCCI Operation Using Different Valving Strategies in a Naturally-Aspirated Gasoline HCCI Engine

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ABSTRACT

Homogenous Charge Compression Ignition (HCCI) combustion offers significant efficiency improvements compared to conventional spark ignition engines. However, due to the nature of HCCI combustion, traditional HCCI combustion can be realized only in a limited operating range. In order to maximize fuel economy benefits the HCCI operating range needs to be extended to higher loads. One immediate benefit is to maximize the portion of the standard driving cycles (NEDC, FTP, etc) that can be run with HCCI combustion, so that transitions between SI operation and HCCI operation can be avoided.

The HCCI operation at high load range is typically limited by a trade-off between combustion noise and combustion stability. In a previous research, we showed how to improve this trade-off using spark-assisted HCCI combustion strategy, and concluded that the HCCI high load operation is limited by the air availability due to a low lift cam when spark-assisted HCCI combustion was applied.

In this research different valving configurations were investigated to maximize the extension of high load limit of HCCI operation. Then two different valving strategies, such as Negative Valve Overlap (NVO) and Positive Valve Overlap (PVO), were compared to improve the efficiency of high load HCCI operation by controlling the amount of internal residual fraction and pumping loss.

When the NVO strategy was employed, as engine load increases, combustion phasing must be retarded to reduce combustion noise due to high amount of hot internal residuals. Retarded combustion phasing at high load HCCI

operation is a key solution for the NVO strategy. On the other hand, when the PVO strategy was applied, optimal residual fraction can be achieved resulting in efficiency improvement due to optimal combustion phasing, lower pumping loss and less heat transfer loss. The high load limit was successfully extended to 10 bar IMEP_g (Gross Indicated Mean Effective Pressure) while maintaining good efficiency and complying with emissions requirements.

INTRODUCTION

SI (Spark-ignition) engines have been the dominant powertrain source for automobiles due to many benefits such as low emissions, relatively simple control, and low cost. However, with evolving CO₂ emissions legislation in Europe, CAFE regulation in the US and rising competition from alternative technologies the SI engine needs to be more fuel efficient to maintain its attractiveness.

There has been a great deal of interest in SI engines operating at lean air-fuel ratios to improve fuel consumption. One of the technologies which have been receiving attention is HCCI, which combines features of the spark ignition and compression ignition (CI) processes. The basic principle of HCCI is that the air and fuel are premixed prior to ignition and then ignited by the compression from the piston motion. The ignition is provided in multiple points and therefore the charge gives a parallel energy release. This results in a uniform and simultaneous auto-ignition throughout the charge without flame propagation, which is relatively fast and more akin to an idealized combustion event [1, 2, 3, 4, 5]. Therefore, more efficient engine operation with lower emissions can be realized.

Some of the earliest studies of HCCI were performed using external Exhaust Gas Recirculation (EGR) in conjunction with inlet air heating in a pre-mixed gasoline research engine operating under lean fuel, wide-open throttle conditions [1, 2]. These studies demonstrated fuel economy equivalent to that of a diesel engine at a limited number of part-load conditions. In recent years, the feasibility of different gas trapping methods that enable HCCI combustion at conventional geometric compression ratio and eliminate the need for auxiliary intake air heating has been extensively studied. One common approach is referred to as the NVO method [6, 7, 8]. In this method, the burned gases trapped inside the cylinder are recompressed and allowed to expand before the intake valve opens. A second method has also been developed and is often referred to as the exhaust gas re-breathing technique, where the exhaust gases are re-inducted directly from the exhaust manifold by re-opening exhaust valve during the intake stroke [9].

Some researchers directly compared the benefits of the NVO and exhaust gas re-breathing methods [10, 11]. These researchers concluded that maximum engine loads achieved through the NVO method are lower than those generated via the re-breathing method, due to earlier and faster combustion resulting from higher in-cylinder gas temperatures and charge stratification effects during negative valve overlap. However, minimum engine loads achieved through the NVO method are also lower than those generated by the re-breathing method. One of the objectives of this paper is to extend high load limit of HCCI combustion without sacrificing the low load performance. Therefore, NVO strategy was adopted due to better performance of light load operation.

Due to the nature of HCCI combustion, robust HCCI operation can be realized only in a limited operating range as shown in Figure 1. The operating range is restricted by misfiring at low load and limited by a high rate of pressure rise at high load. A major target in applying HCCI for commercial use is to expand the operating range in order to cover an increased portion of the driving cycles. Recently, the authors successfully extended the low load limit by developing HCCI combustion at idle using a multiple injection and multiple ignition (MIMI) strategy combined with fuel reforming [12, 13].

In order to extend high load operating limit, several strategies have been proposed in the literature. For example, increasing the potential operating range of HCCI combustion through the use of turbo-charging or supercharging has been considered [14, 15, 16, 17]. Increasing the intake air pressure raises the air mass flow through the engine while the highly diluted conditions required to avoid knock can be maintained. Other methods that have been used to increase the HCCI operating window include variable compression ratio [18], spark-assisted operation [19], and charge stratification [20].

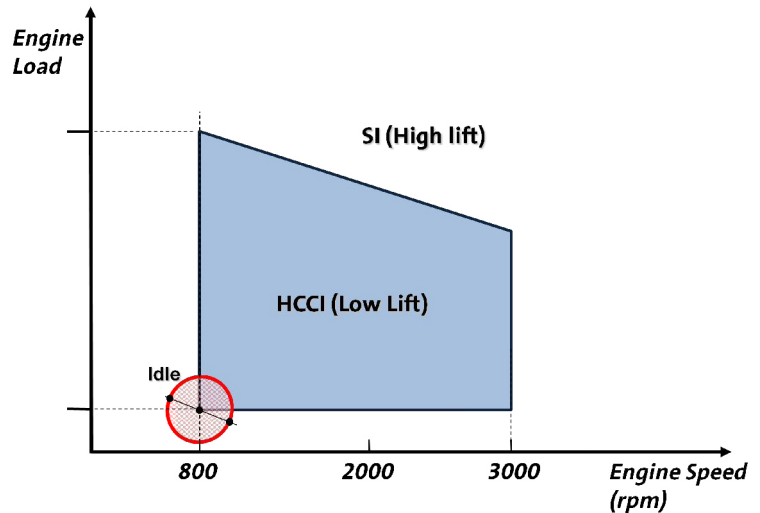


Figure 1. Representation of the limited operating range of robust HCCI operation in a conventional 4-stroke engine

The main obstacle to achieve HCCI combustion at high load operation is a trade-off between combustion noise (ringing) and combustion stability (COV of IMEP). The authors showed how to improve this trade-off using spark-assisted HCCI combustion strategy in a previous report [21]. By adopting spark-assisted HCCI strategy and combustion phasing control algorithm, the HCCI high load operation is limited by the air availability [22]. In order to overcome the limit of air availability, a different valve profile was used to investigate the overall performance of spark-assisted HCCI combustion at high load operation using NVO strategy.

Since internal residual fraction and external EGR rate are critical parameters at high load spark-assisted HCCI operation, valving strategies to control the dilution of in-cylinder charge play an important role on HCCI performance. Therefore, this research focuses on comparison of two different valving strategies for optimizing a spark-assisted HCCI combustion operated at high load condition, which is one of the efforts to further extend the high load operating limit of HCCI combustion.

EXPERIMENTAL SETUP

The engine used in these experiments was a single cylinder four-stroke engine. The prototype cylinder heads were equipped with four valves per cylinder and direct fuel injection. The compression ratio was 12.0:1. The configuration of piston, spark plug position and injector position was designed to enable stratified charge combustion. The specifications of the engines are given in Table 1.

The single-cylinder engine was equipped with a Fully Flexible Valve Actuation (FFVA) system. The real time valve motion is detected by one Linear Variable

Displacement Transducer (LVDT) per valve and one accelerometer. The peak valve lift of intake and exhaust valves was varied based on the strategy. In NVO strategy, the peak valve lift of intake and exhaust valves was 5.0 mm and 6.0 mm, respectively, and the opening duration of intake and exhaust valve was 145 and 160 crank angle degrees (CAD), respectively. Low lift valve profile was designed considering the compatibility with a two-step mechanism. In PVO strategy, the same valve profiles as conventional SI operation were used, which are 10 mm of peak valve lift and 240 CAD of valve duration for both intake and exhaust valves.

The injector used in these experiments was an 8-hole solenoid actuated injector. The fuel injection pressure was maintained at 12 MPa. The fuel used was a fully blended gasoline with octane number $(RON(90.9)+MON(83.2))/2$ of 87. The engine coolant and engine oil were set to 95 deg C. The cylinder pressure was measured with a Kistler 6125A pressure transducer. Exhaust emissions were sampled from a mixing plenum in the exhaust system and analyzed by a Horiba Mexa 7000 exhaust gas analyzer. The air fuel ratio in the exhaust was measured with a wide-range air-fuel sensor (in addition to the calculation from the exhaust emissions). The air flow to the engine was measured with sonic nozzles, and a plenum was used to dampen the pressure pulsations in the intake. The plenums are equipped with heaters so that the intake air can be heated even though no additional heating was used in these experiments. The intake manifold pressure was measured with a Sensotec strain gage absolute pressure transducer.

Table 1. Engine specifications

Engine Type	4 valve DOHC gasoline
Bore	86.0 mm
Stroke	94.6 mm
Compression Ratio	12.0 : 1
Intake Valve Lift (NVO / PVO)	5.0 mm / 10.0 mm
Exhaust Valve Lift (NVO / PVO)	6.0 mm / 10.0 mm
Intake Valve Opening Duration	145 CAD / 240 CAD
Exhaust Valve Opening Duration	160 CAD / 240 CAD
Injector Type	Multi-hole solenoid
Injection Pressure	12 MPa
Number of nozzle hole	8
Included Spray Angle	60 deg

The heat release calculation was performed according to the first law of thermodynamics. The heat transfer was accounted for whereas blow-by is assumed to be negligible and not taken into account for the heat release calculation. The heat transfer calculation used the heat transfer coefficient correlation proposed by Woschni [23] with a slight modification of the velocity term. The residual gas fraction was estimated using the correlation published by Yun and Mirsky [24]. The operating conditions for the present experiments are listed in Table 2. The engine speed was 2000 RPM. The intake manifold pressure was maintained at 97 kPa. The valve timings and the EGR rate were adjusted for each experiment.

Table 2. Operating conditions

Engine Speed	2000 RPM
Fuel Flow	20 – 32 mg/cycle
Intake Temperature	30 - 60°C (varies with amount of EGR)
Coolant Temperature	95 °C
Oil Temperature	95 °C
Intake Manifold Pressure	97 kPa

RESULTS AND DISCUSSION

HCCI engine operation is mostly known for its very low NO_x emissions even with lean air-fuel mixtures. However, as the amount of fuel mass injected into the cylinder is increased, the NO_x emissions increase due to locally available hot spot generated by the incremented inhomogeneity, and will reach unacceptably high levels without adequate after-treatment systems. Figure 2 shows the NO_x emissions measured in a single cylinder engine as a function of engine load at 2000 rpm. As such, the following experiments are performed at a stoichiometric HCCI operation to enable NO_x reduction with conventional three-way catalysts. The reported emissions in this paper are engine-out emissions.

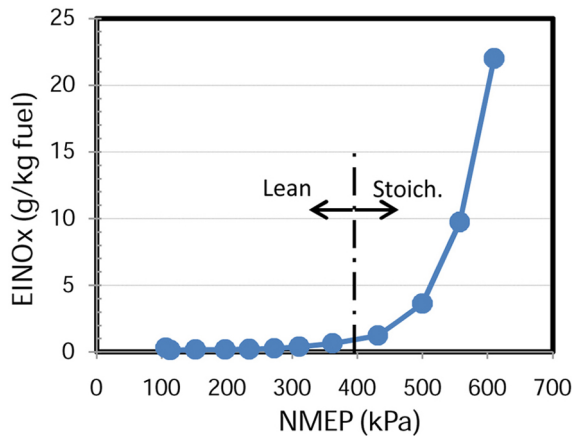


Figure 2. NOx Emissions obtained in a single cylinder engine as a function of engine load at 2000 rpm

The purpose of this research is to suggest solutions for optimal performance of a spark-assisted stoichiometric HCCI combustion at high load operating condition. Since HCCI combustion is sensitive to the temperature, pressure and composition of the charge, the control of the in-cylinder charge has a significant effect on HCCI combustion. Hot internal residual fraction and relatively cold external EGR determine a dilution level of the in-cylinder charge, which influences the in-cylinder charge temperature as well as oxygen concentration. In order to investigate the effect of in-cylinder charge condition, two different valving strategies are compared; one is NVO strategy and the other is PVO strategy.

A single-cylinder engine equipped with FFVA system was used for all the tests. The experiments are performed at 2000 rpm. In order to evaluate the combustion noise, ringing index is used in this study [25]. Ringing index is defined as

$$RI = 2.88 \times 10^{-8} \times \frac{(MPRR \times RPM)^2}{PP}$$

where MPRR is the maximum pressure rise rate, RPM is the engine speed, and PP is the peak pressure.

Negative Valve Overlap (NVO) Strategy with low lift valve

In NVO strategy, exhaust valve closing (EVC) timing determines the internal residual (hot residual gas) mass fraction. The decreasing residual gas fraction means that more air is inducted in the cylinder, which changes the mixture A/F ratio. Since EGR rate gives additional dilution to the charge, in order to maintain the stoichiometric operation, EGR rate should be adjusted. Therefore, as engine load (injected fuel mass) changes, either the amount of NVO or EGR rate should be varied. Figure 3 shows the variation of NVO and EGR as a function of engine load. As engine load increases, both NVO and EGR rate were reduced

simultaneously, which will influence the combustion phasing of HCCI combustion due to the change of in-cylinder combustion temperature.

It is well known that combustion noise (ringing index) is closely related with the combustion phasing and spark timing plays an important role on controlling the combustion phasing at spark-assisted stoichiometric HCCI combustion at high load condition [21, 22]. In addition, in order to achieve robust spark-assisted HCCI operation at high load, combustion phasing control is very critical. Therefore, in order to maintain low ringing level at high load HCCI operation, combustion phasing should be retarded using spark timing. The variation of spark timing and associated combustion phasing at 2000 rpm are presented in Figure 4. As engine load increases, combustion phasing was retarded to avoid high ringing operation by retarding spark timing. The most retarded combustion phasing was carefully selected considering combustion stability.

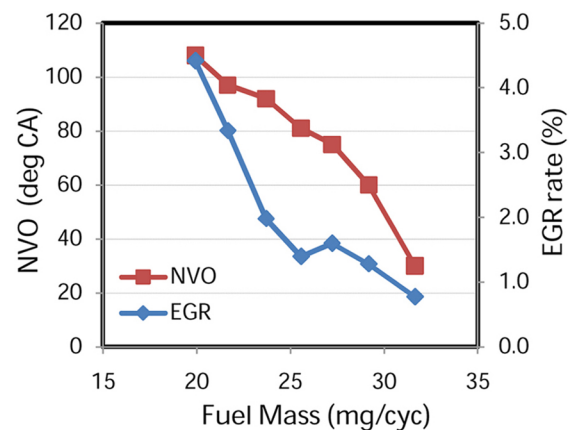


Figure 3. The variation of NVO and external EGR as a function of engine load at 2000 rpm

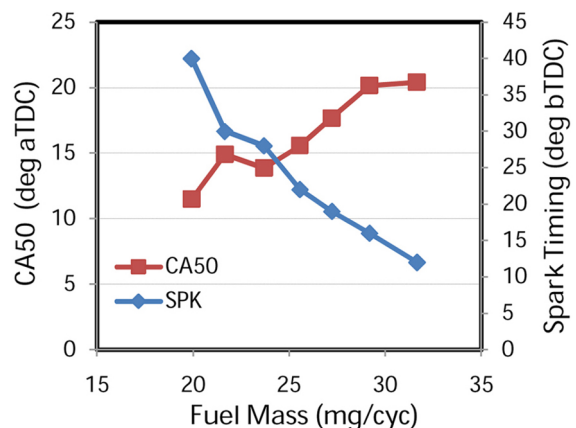


Figure 4. The variation of combustion phasing together with the spark timing as a function of engine load at 2000 rpm