

Extending the High Load Operating Limit of a Naturally-Aspirated Gasoline HCCI Combustion Engine

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ABSTRACT

Homogenous Charge Compression Ignition (HCCI) combustion offers efficiency improvements compared to conventional gasoline engines. However, due to the nature of HCCI, traditional HCCI combustion can be realized only in a limited operating range. The HCCI operation at high load is limited by excessive combustion noise.

In order to maximize the fuel economy benefits of HCCI its operating range needs to be extended to higher loads. In particular, one immediate benefit of an increased load range on the NEDC driving cycle is the avoidance of transitions between SI operation and HCCI operation.

In this research a detailed investigation of the fundamental reasons for high combustion noise was performed. Spark-assisted HCCI combustion was found to be a key factor to reduce combustion noise at high load condition. Injection timing for charge cooling, spark timing for the onset of combustion through flame propagation, smaller NVO and higher EGR are the enablers to achieve the appropriate spark-assisted HCCI combustion at high load operation. The high load limit was successfully extended while maintaining good efficiency and complying with emissions regulations.

The effect of double injection strategy was also investigated. It is found that even though slight improvement in the trade-off between combustion noise and combustion stability can be achieved through double injection strategy, fuel consumption is deteriorated due to incomplete combustion.

INTRODUCTION

Gasoline SI (Spark-ignition) engines have been the dominant power 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 legislation in the US and rising competition from alternative technologies such as diesel engines and hybrid electric powertrains, the gasoline engine needs to be more fuel efficient to maintain its attractiveness.

There has been a great deal of interest in gasoline engines operating at lean air-fuel ratios to improve fuel consumption. One of the technologies which has been receiving attention is Homogeneous Charge Compression Ignition (HCCI), which combines features of the spark ignition and compression ignition (CI) processes. The basic principle of HCCI is, either in gasoline [1,2,3,4] or diesel [5,6,7,8] engines, 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 and chemical reaction throughout the whole charge without flame propagation, which is relatively fast and more akin to an idealized combustion event.

HCCI combustion concepts offer the benefit of reduced fuel consumption and low engine-out NO_x emissions over the conventional SI combustion mode, therefore avoiding expensive exhaust after-treatment which is necessary for most lean combustion engines [1,2,3,4].

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 [9, 10]. 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 negative valve overlap (NVO) method [11,12,13]. 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-induced directly from the exhaust manifold by re-opening exhaust valve during the intake stroke [14].

Some researchers directly compared the benefits of the NVO and exhaust gas re-breathing methods [15, 16]. 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 considering better performance of light load operation in this research.

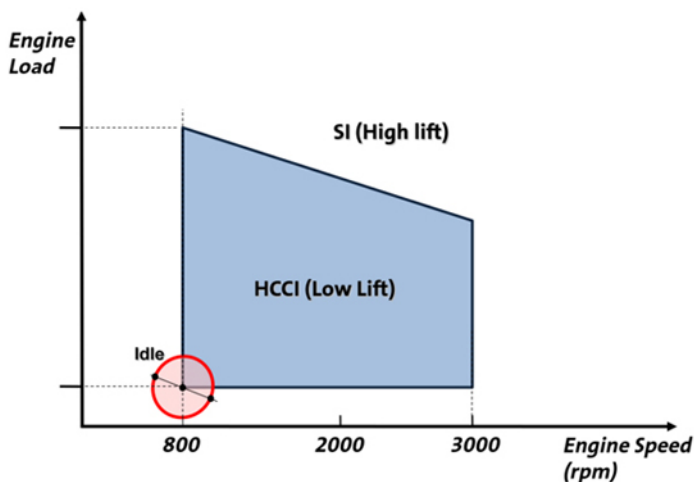


Figure 1. Representation of the limited operating range of robust HCCI operation in a conventional 4-stroke engine

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 various 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 [17, 18].

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 [19,20,21,22]. 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 [23], spark-assisted operation [24], charge stratification [25], and varying coolant temperature [26].

The main obstacle to achieve HCCI combustion at high load operation is very fast pressure rise rate due to the characteristics of auto-ignition. In order to decrease the pressure rise rate, combustion phasing should be retarded. However, retarded combustion phasing can cause an efficiency drop and ultimately leads to unstable combustion. This research relates to a method for optimizing the trade-off between combustion stability and combustion noise by employing a spark-assisted HCCI combustion strategy, which is one of the efforts to further extend the high load operating limit of HCCI combustion.

EXPERIMENTAL SETUP

The engines used in these experiments were a single cylinder four-stroke engine and a 2.2 L four-cylinder four-stroke engine that share the same combustion chamber geometry. 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](#).

Table 1. Engine specifications

Engine Type	4 valve DOHC gasoline
Bore	86.0 mm
Stroke	94.6 mm
Compression Ratio	12.0 : 1
Intake / Exhaust Valve Lift	3.5 mm
Valve Opening Duration	120 CAD
Injector Type	Multi-hole solenoid
Injection Pressure	12 MPa
Number of nozzle hole	8
Included Spray Angle	60 deg

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 four-cylinder engine was operated with fixed overhead cams and an electric cam phaser which has a 90 crank angle degree authority. The intake and exhaust cam shafts for this experiment were designed for negative valve overlap (NVO) operation. The negative valve overlap is defined as the crank angle duration between the closing of the exhaust valves and the opening of the intake valves. The peak valve lift was 3.5 mm and the opening duration 120 crank angle degrees for both intake and exhaust valves.

The injectors used in these experiments were solenoid 8-hole injectors with 60 degree spray angle. 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. The intake manifold pressure was measured with a Sensotec strain gage absolute pressure transducer.

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 [27] with a slight modification of the velocity term. The residual gas fraction was estimated using the correlation published by Yun and Mirsky [28].

The operating conditions for the present experiments are listed in Table 2. The engine speed was 2000 or 2500 RPM. The fuel flow varies between 12 and 16 mg fuel per cylinder per cycle. 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, 2500 RPM
Fuel Flow	12 – 16 mg/cycle
Intake Temperature	30 °C (varies with amount of EGR)
Coolant Temperature	95 °C
Oil Temperature	95 °C
Intake Manifold Pressure	97 kPa

Although 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 lean NO_x after-treatment. Figure 2 shows the NO_x emissions measured at single cylinder engine as a function of engine load at 2000 rpm. As such, the following experiments are performed as a stoichiometric HCCI operation to enable NO_x reduction with conventional three-way catalysts. The reported emissions in this paper are engine-out emissions.

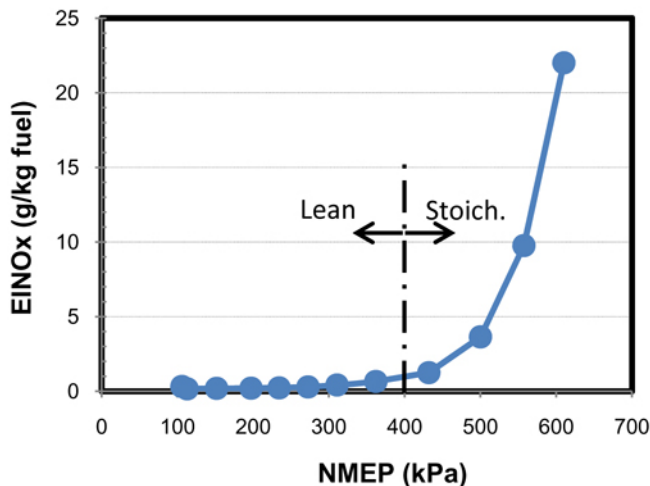


Figure 2. NOx Emissions obtained at single cylinder engine as a function of engine load at 2000 rpm

The first part of the investigation is performed on the single cylinder engine and addresses the effect of internal residuals, external EGR, injection timing and spark timing on the stoichiometric HCCI operation, especially the heat release rate and the burn duration. First NVO sweeps are performed at different fueling levels where the EGR rate is adjusted to maintain a stoichiometric mixture. Then the effect of injection timing is investigated. Finally, spark sweeps are performed without maintaining combustion phasing first and the NVO and EGR are adjusted to maintain a stoichiometric mixture as well as a fixed combustion phasing (CA50).

Based on the results obtained from the single-cylinder engine, more extensive experiments are performed at the multi-cylinder engine. The main focus was to find out the method to reduce combustion noise without sacrificing the combustion stability. First the combined influence of the NVO, EGR, injection timing and spark timing on the combustion characteristics is investigated. In the next step the effect of multiple injections is addressed.

RESULTS AND DISCUSSION

The focus of this research is two-fold; one is to understand the characteristics of spark-assisted stoichiometric HCCI combustion and the other is to suggest solutions to extend the operating range of spark-assisted stoichiometric HCCI.

Single Cylinder Results

In order to understand the fundamental characteristics of spark-assisted stoichiometric HCCI combustion, a single-cylinder engine equipped with fully variable valve system was used. The experiments are performed at 2000 rpm. In order to evaluate the combustion noise, ringing index is used in this study [31]. 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.

Effect of NVO and EGR - In NVO strategy, exhaust valve closing (EVC) timing determines the trapped residual mass fraction. EGR rate gives additional dilution to the in-cylinder charge. The increasing residual gas fraction means that less air is inducted in the cylinder, which leads to rich combustion. Therefore, various combinations of NVO and EGR are possible to achieve stoichiometric HCCI operation at a given fuel mass, injection timing and spark timing.

In order to investigate the effect of internal residual and external EGR, the amount of NVO was varied while adjusting EGR rate for stoichiometric operation for a given fuel mass. Injection timing and spark timing were fixed at 310 deg bTDC and 30 deg bTDC, respectively.

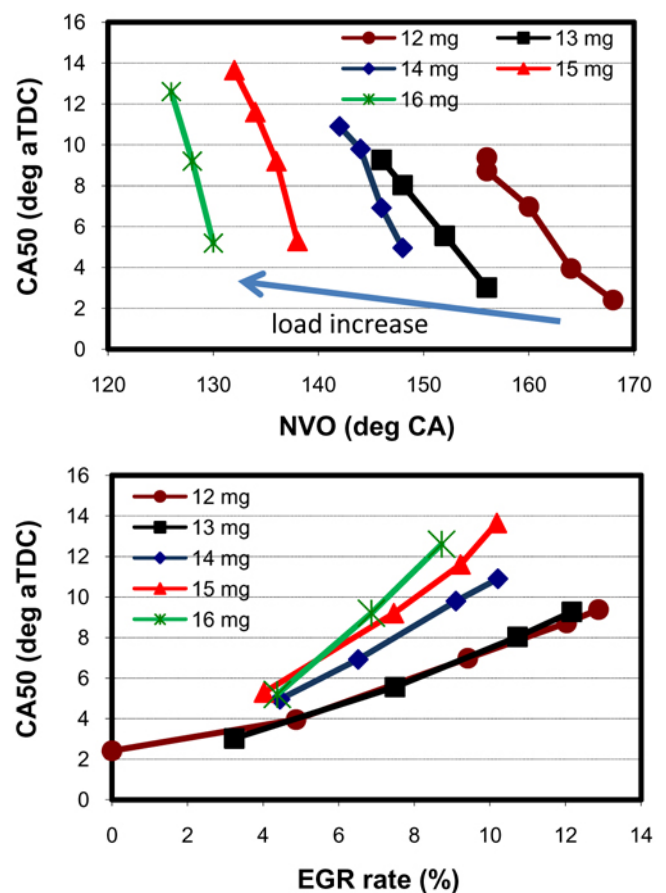


Figure 3. The effect of NVO and external EGR on combustion phasing at 2000 rpm

Figure 3 presents the effect of NVO and EGR on combustion phasing. As NVO increases or EGR decreases, combustion phasing (CA50) is advanced. As NVO increases, the amount of hot trapped residual mass in the cylinder is increased due to the shortening of the exhaust stroke, while cold external EGR mass is decreased. Therefore, as NVO increases, the thermal content of the in-cylinder charge at IVC is increased, resulting in more advanced combustion phasing (higher ringing).

The effect of the combustion phasing on ringing is shown in Figure 4. Ringing monotonically increases as combustion phasing is advanced regardless of the injected fuel mass. In order to maintain low level of ringing index, combustion phasing should be retarded. However, when combustion phasing is too retarded, efficiency will drop and combustion will eventually become unstable.

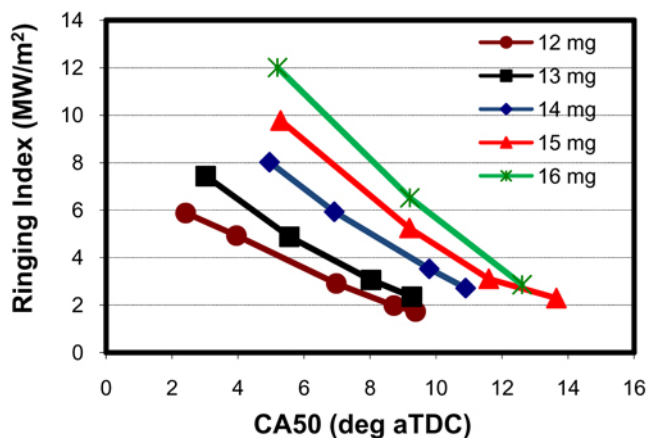


Figure 4. The effect of combustion phasing on combustion noise (ringing index) at 2000 rpm

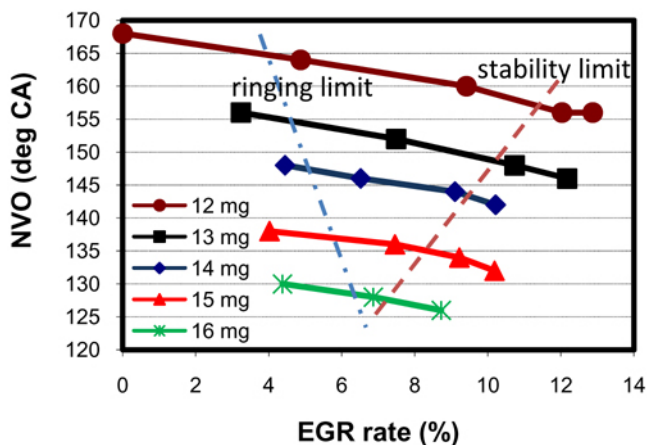


Figure 5. The ranges of NVO and EGR for a given fuel mass, injection timing and spark timing at 2000 rpm.

Figure 5 shows the possible ranges of NVO and EGR for a given fuel mass including the border-line determining the ringing limit and stability limit. As EGR decreases, NVO should increase to maintain stoichiometric operation at a given fuel mass. As engine load (injected fuel mass) increases, the ranges of NVO and EGR combination becomes smaller. For a given fuel mass, maximum NVO and minimum EGR is limited by advanced combustion phasing (high ringing), which is presented with a blue dotted line in the plot. Minimum NVO and maximum EGR is restricted by retarded combustion phasing (high instability), which is shown with a red dotted line in the graph. Ultimately only very small variations of NVO and EGR are allowed to run the engine properly, which limits high load HCCI operation. When NVO or EGR changes slightly, ringing is sharply increased or combustion stability is abruptly deteriorated. For example, at 16 mg of fuel mass, combustion becomes very sensitive to even 2 deg CA change of NVO or 1% variation of EGR.

Therefore, the purpose of this research is to improve the trade-off between combustion stability and combustion noise at high load HCCI operation by finding a way to reduce the ringing index with acceptable stability.

Effect of Injection Timing - In order to examine the effect of injection timing, injection timing was changed from 280 deg bTDC to 350 deg bTDC. Engine operating condition is 2000 rpm, 14 mg of fuel mass. NVO and the spark timing were fixed while EGR was adjusted for stoichiometric operation.

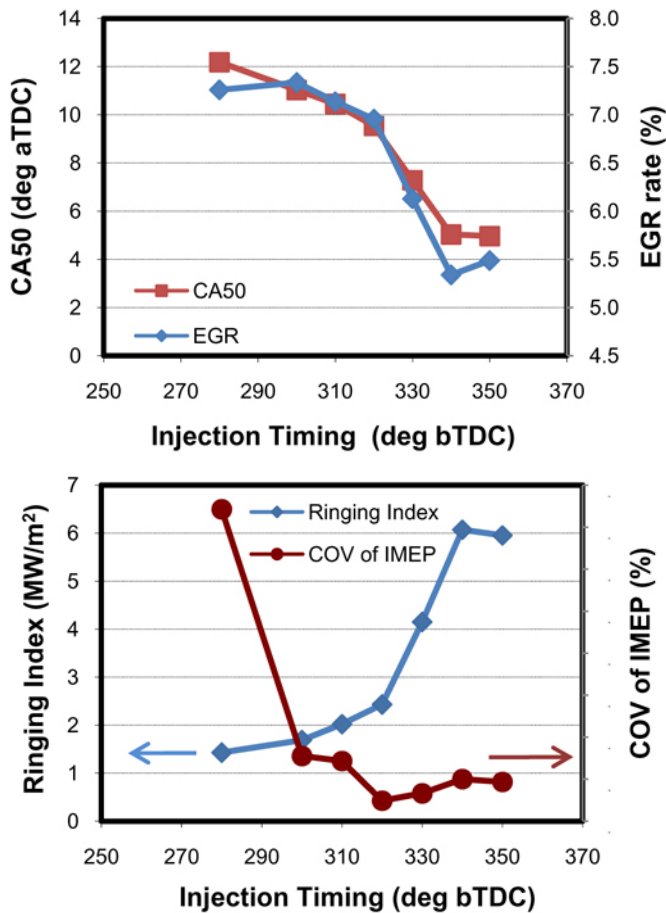


Figure 6. The effect of injection timing on combustion characteristics and external EGR rate

Figure 6 shows the effect of injection timing on the combustion phasing and EGR rate. The associated effect on ringing and combustion stability (COV of IMEP) is also plotted in the graph. As injection timing is retarded (further away from the recompression top dead center), the combustion phasing is retarded, and the amount of EGR inducted into the cylinder for stoichiometric operation is increased. Due to the retarded combustion phasing, ringing is decreased, but combustion stability is degraded. This might have two causes; one is varying levels of charge stratification and the other is a different amount of EGR.

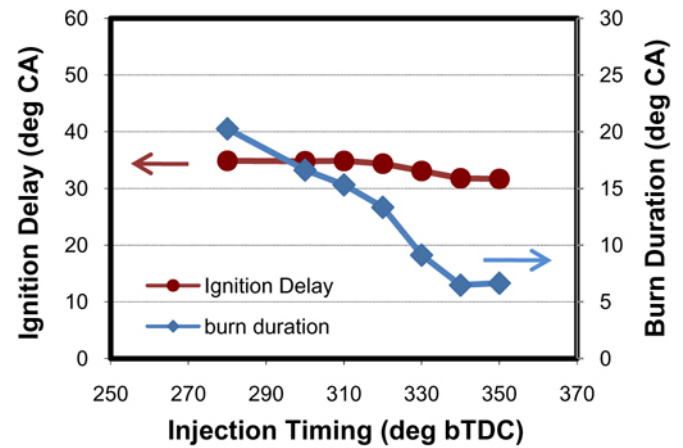


Figure 7. The effect of injection timing on ignition delay and the total burn duration

To understand the effect of the injection timing on combustion phasing, pressure traces were analyzed and heat release rates were calculated. Figure 7 presents the effect of the injection timing on the ignition delay and the total burn duration. Ignition delay is defined as the crank angle between the spark timing and CA10 and the total burn duration is defined as the crank angle between CA10 and CA90. Cylinder pressures, the associated heat release rates and mass fraction burns as a function of the injection timing are plotted in Figure 8. As can be seen in Figure 7, ignition delay changes little as a function of the injection timing, which means the onset of the combustion does not change when the injection timing varies. However, total burn duration is extended as the injection timing is retarded, which indicates chemical kinetics (burn rate) becomes slower due to the increased amount of EGR inducted into the cylinder. The effect of injection timing on the combustion phasing and the total burn duration can be more clearly seen in Figure 8. As injection timing is advanced, both peak pressure and the peak heat release rate are increased, which indicates the advanced combustion phasing. In addition, as combustion phasing is advanced, the total burn duration is shortened, which helps to increase the ringing level further. Therefore, low level of ringing can be achieved at retarded injection timing due to retarded combustion phasing and extended total burn duration caused by the increased amount of external EGR, but combustion stability still would be an issue. The effect of EGR on combustion characteristics is stronger than that of charge stratification at this operating condition. In conclusion, injection timing is one of the key parameters that have an impact the combustion phasing (CA50) at high load HCCI operation.