

Comparative Study on Gasoline HCCI and DICI Combustion in High Load Range with High Compression Ratio for Passenger Cars Application

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ABSTRACT

This study compared the combustion and emission characteristics of Homogeneous Charge Compression Ignition (HCCI) and Direct Injection Compression Ignition (DICI) modes in a boosted and high compression ratio (17) engine fueled with gasoline and gasoline/diesel blend (80% gasoline by volume, denoted as G80). The injection strategy was adjusted to achieve the highest thermal efficiency at different intake pressures. The results showed that Low Temperature Heat Release (LTHR) was not observed in gasoline HCCI. However, 20% additional diesel could lower down the octane number and improve the autoignition reactivity of G80, which contributed to a weak LTHR, accounting for approximately 5% of total released heat.

The combustion efficiency in gasoline DICI was higher than those in gasoline HCCI and G80 HCCI, while the exhaust loss and heat transfer loss in DICI mode were higher than those in HCCI mode. Increasing intake pressure improves the Indicated Thermal Efficiency (ITE) in both HCCI and DICI mode, and when the intake pressure was 2.1 bar, gasoline DICI achieved the highest ITE of 49.3%, while the ITE of G80 HCCI was the lowest of 47.7%. When the intake pressure was increased, earlier CA50 and longer combustion duration were observed in HCCI mode, while only slight change in CA50 for DICI mode was observed and the combustion duration became shorter. CO and HC emissions in gasoline DICI were dramatically lower than those in gasoline HCCI and G80 HCCI. However, gasoline DICI resulted in NO_x and soot emissions, while gasoline HCCI achieved near-zero NO_x and soot emissions.

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INTRODUCTION

With the increasingly stringent regulations on fuel consumption and emissions, various high efficiency and low emission combustion modes have been investigated to meet the future challenges. Homogeneous Charge Compression Ignition (HCCI) has been studied nearly 40 years [1, 2, 3]. Homogeneous charge can be achieved by port injection, umbrella direct injection and multiple direct injection in the intake stroke, so as to achieve fast and low-temperature combustion near Top Dead Center (TDC), resulting in high thermal efficiency and ultra-low NO_x and soot emissions. However, several concerns have to be overcome for practical application: 1) high CO and HC emissions decrease combustion efficiency, which hinders further improvements in thermal efficiency; 2) high Maximum Pressure Rise Rate (MPRR) makes it difficult to extend the load range; 3) the control of HCCI combustion is difficult. Some improvements have been made through the use of charge stratification [4, 5], spark assist [6, 7], and intake boosting [8]. Partially Premixed Compression Ignition (PPCI), proposed by Kalghatgi [9, 10], can form charge stratification before combustion by injecting fuel in the compression stroke. This helps reduce the heat

release rate and therefore decrease the MPRR. Moreover, the premixed mixture can avoid diffusion combustion, resulting in lower soot emission. However, when exploring the maximum thermal efficiency, advanced CA50 and short combustion duration are required, which leads to extremely high MPRR and unacceptable combustion noise, since both HCCI and PPCI combustion occur within a very short time. Thus, Multiple Premixed Compression Ignition (MPCI) was proposed by Yang [11] in order to lower MPRR and extend load range by dividing the combustion process into two stages. The first stage combustion is premixed combustion, while the second stage combustion is partially premixed combustion [12]. Although two stage combustion process prolongs the combustion duration, early CA50 and high combustion efficiency can counteract the negative influence caused by longer combustion duration and even improve fuel consumption.

High octane number gasoline has long ignition delay and thus can form more premixed mixture, which leads to high thermal efficiency and low soot emission [13, 14, 15]. For example, Gasoline Direct Injection Compression Ignition (GDICI) by Sellnau et al. achieved

Indicated Thermal Efficiency (ITE) of 48.3% and ultra-low NO_x and soot emissions simultaneously at 2000 r/min and 11 bar IMEP on the second generation GDCI engine with compression ratio of 15 and fueled with RON 91 gasoline blended with 10% ethanol [14]. Low octane number gasoline can promote combustion stability and extend to low load due to better ignitability [16]. One common way to obtain low octane number gasoline is blending gasoline with diesel [17, 18, 19]. Further, diesel can improve the ignitability of low octane number gasoline, but may increase the soot emission due to the poor volatility.

Gasoline HCCI combustion has been widely studied in gasoline spark ignition engines with low compression ratio (about 10) at low load range (2~5 bar BMEP) for passenger cars. It has been demonstrated that 15%-33% reduction of fuel consumption is achieved compared to conventional SI combustion by AVL, GM, Tsinghua [20, 21, 6]. However, few studies focus on gasoline HCCI with high compression ratio (17 above) at high load range for passenger cars.

This study investigated gasoline HCCI, low octane number gasoline (G80, 80% gasoline+20% diesel by volume) HCCI, and gasoline Direct Injection Compression Ignition (DICI) to explore the highest achievable thermal efficiency for passenger cars application. The engine load was selected as 11 bar IMEP according to the common used operation point in dedicated engine for hybrid vehicles.

The combustion and emission characteristics of two combustion modes and two fuels were compared. The differences of the thermal efficiency were analyzed from the perspective of fuel energy utilization.

EXPERIMENTAL SETUP

Apparatus

The study was conducted in a four-stroke, water-cooled, single-cylinder direct injection diesel engine, which was retrofitted from a Euro IV four-cylinder engine by deactivating cylinders 2, 3 and 4. Figure 2 shows the schematic of the experimental setup. The engine specifications are listed in Table 1. The turbocharger was removed and an external air compressor was used for intake boosting. The intake and exhaust surge tanks were used to reduce air flow pulsation and decrease the measurement uncertainties of air flow, intake pressure, and exhaust pressure. A port fuel injector was adopted to form homogeneous charge in HCCI mode. The in-cylinder pressure was measured with an AVL GH14P cylinder pressure transducer. 100 consecutive cycles were recorded for combustion analysis. Exhaust emissions, including CO, HC, CO₂, NO_x, were measured by AVL CEB II pollutants analyzer. AVL 439 opacimeter was used for soot emission measurement and the measurement unit is m⁻¹. In order to achieve the highest thermal efficiency, the original ω -shaped diesel piston was replaced by a low heat transfer piston as shown in Figure 1.

Table 1. Engine specifications

Engine type	single cylinder, light-duty diesel engine
Stroke (mm)	92.0
Bore (mm)	83.1
Connecting rod length (mm)	145.1
Displacement (L)	0.498
Compression ratio	17:1
Injection system	common rail, direct injection (600 bar) / port fuel injection (3 bar)
Intake valve open (deg BTDC)	24
Intake valve close (deg ABDC)	50
Exhaust valve open (deg BBDC)	86
Exhaust valve close (deg ATDC)	16

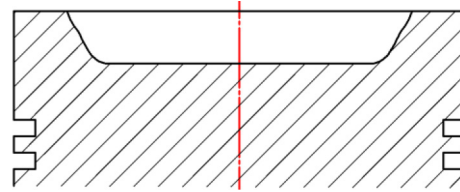


Figure 1. Low heat transfer piston

Test Fuels

Gasoline was tested in HCCI mode and DICI mode, while G80 was tested in HCCI mode. The tested gasoline was commercial gasoline in China with Research Octane Number (RON) of 92. Considering the low viscosity of gasoline, 200 ppm alkoxy long-chain alkyl amide, supplied by Afton Chemical Corporation, was added into gasoline to protect the fuel pump in DICI mode, since the injection pressure was much higher than that in HCCI mode. Table 2 lists the properties of gasoline and diesel.

Table 2. Fuel properties of gasoline and diesel

Fuel	gasoline	diesel
Cetane number	--	56.5
Research octane number	92.0	--
LHV (MJ/kg)	42.95	42.68
Density (g/cm ³)	0.747	0.830
10% evaporation temperature (°C)	48.8	223.2
50% evaporation temperature (°C)	99.5	265.5
90% evaporation temperature (°C)	168.9	310.5

Test Methods

The aim of this study is exploring the maximum thermal efficiency of different combustion modes, including gasoline HCCI, G80 HCCI, and gasoline DICI, and comparing the combustion and emission characteristics. Engine speed was fixed at 2000 r/min. The intake pressure varied from 1.7 to 2.1 bar in interval of 0.1 bar. The temperature of intake fresh air and cooling water was 23°C and 75°C,

respectively. Exhaust Gas Recirculation (EGR) was not applied, and IMEP COV was maintained below 3%, and the upper limit of MPRR was set at 10 bar/deg.

Port fuel injection was adopted in HCCI mode and the injection pressure was 3 bar. A double injection strategy and common rail direct injection with the pressure of 600 bar were used in DICI mode. It has been demonstrated that too early first injection timing would lead to high CO and HC emissions and consequently low combustion efficiency, while late first injection timing results in high MPRR and combustion noise. Early second injection timing leads to high MPRR and NO_x emission, while late second injection timing results in low combustion temperature and low thermal efficiency [18]. Considering this, the first injection timing ranged from -50 to -25 deg After Top Dead Center (ATDC) and the second injection timing ranged from -10 to -2 deg ATDC, with the split ratio of 40:60. The fuel injection rate varied from 1.6 to 1.8 kg/h to maintain IMEP around 11 bar, and the equivalence ratio varied from 0.32 to 0.42. For each specific

intake pressure, operating points with the maximum thermal efficiency were chosen and analyzed for the comparison of different combustion modes and fuels.

RESULTS AND DISCUSSION

Combustion Characteristics of Gasoline HCCI, G80 HCCI and Gasoline DICI

Figure 3 shows the curves for in-cylinder pressure and heat release rate of gasoline HCCI, G80 HCCI, and gasoline DICI. Low Temperature Heat Release (LTHR) is not observed in gasoline HCCI. But in G80 HCCI, a weak LTHR is observed and accounts for 4-6% of total released heat as Figure 3(b) and 3(d) show. When intake pressure increases, the peak heat release rate of LTHR increases and the phase is advanced. The phase of High Temperature Heat Release (HTHR) of gasoline and G80 HCCI also advances with increased intake pressure, which favors thermal efficiency. As for gasoline DICI, the increased intake pressure retards the combustion phase and lower peak heat release rate of the first stage combustion, while the intake pressure has slight influence on the second stage combustion.

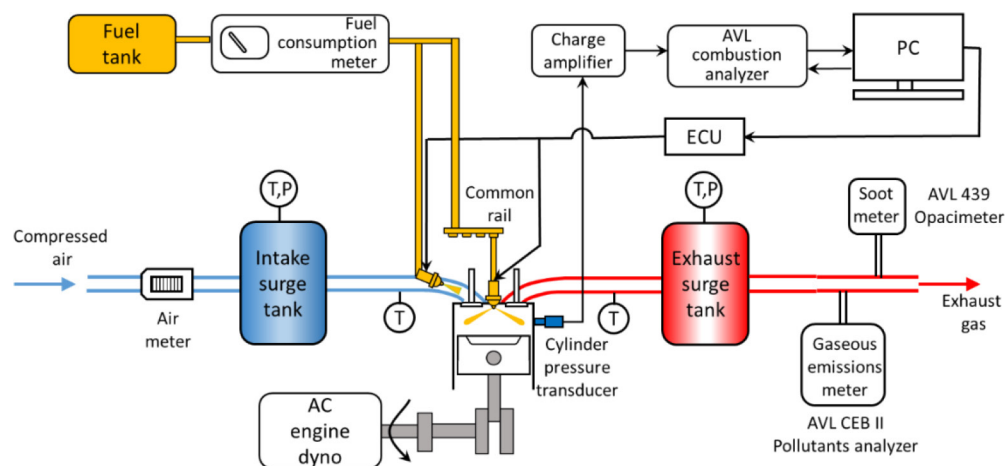
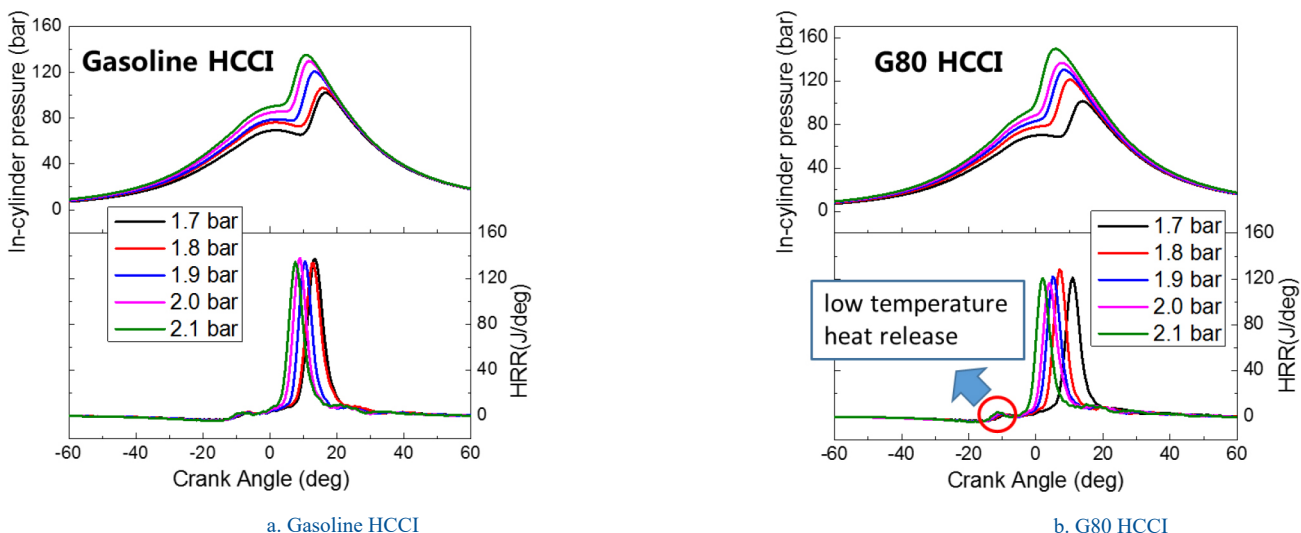


Figure 2. Schematic of experiment bench



a. Gasoline HCCI

b. G80 HCCI