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Comparison of HCCI and SI Characteristics on Low Load CNG-DI Combustion

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Abstract: This paper compares the combustion characteristics of CNGDI by pilot homogeneous charge compression ignition of gasoline and combustion of CNGDI by spark ignition. Homogeneous charge of gasoline is created by injecting the fuel in the manifold and the charge is heated by an air heater in order to achieve HCCI combustion of gasoline that ignites the direct injected and stratified CNG at 80 BTDC. The combustion characteristics obtained are compared with that of CNG by spark ignition. The results show that there are significant effects on HC, CO and NOx emissions. HCCI combustion has higher fuel conversion efficiency compared SI and less emissions within certain range of loads.

Key words: Homogeneous charge compression ignition, compress natural gas, gasoline, spark ignition

INTRODUCTION

Natural gas vehicles are becoming popular in geographic locations where natural gas is widely available. Natural gas as an alternative fuel has been applied in spark ignition engine to reduce the engine emissions. Natural gas engine comes with a drawback in engine performance compared to gasoline and diesel engine due to lower volumetric efficiency, lower energy content, and longer combustion durations. However, higher octane number of natural gas compare to gasoline is beneficial to increase engine efficiency. Most of the vehicles that convert to natural gas system are still using port injection or carburetors. Applying direct injection system on natural gas engine will increase the volumetric efficiency of the engine and further increase the engine performance; while still maintaining the low engine emissions (Firmansyah, 2007; Hassan, 2008).

HCCI has the characteristic of two most popular forms of combustion used in internal combustion engines as in Fig. 1; spark ignition (gasoline engine) and stratified charge compression ignition (diesel engine). HCCI is achieved when a pre-mixed charge of air, fuel and recycled combustion products is auto-ignited by compression in a reciprocating engine. Auto-ignition of HCCI depends on the pressure and temperature of the unburnt fuel/air mixture. In SI engine, fuels needs to be resistant to auto ignition whereas in conventional CI engine fuel should auto-ignite readily. The auto-ignition phenomena of HCCI will vary very widely across different fuel quality together with the engine design and operating conditions Kalghatgi (2007).

The main feature of HCCI combustion of becoming an interest subject to the present combustion engine development is that HCCI auto-ignition can be achieved with very lean overall mixtures (much leaner than can be ignited with a spark) which alleviates the throttling requirement at low engine loads. This results in a distributed reaction of the mixture which occurs at relatively low temperatures, and prevents the formation of NOx emissions, thus eliminating the need for catalytic NOx reduction from the exhaust gas Thring (1989). For this reason, HCCI combustion has received much attention and has been the subject of numerous investigations in internal combustion engines. On the other hand, HCCI combustion of stoichiometric or fuel-rich mixtures results in a very high heat release rates that create excessive cylinder pressures and combustion noise. Many researchers have reported "knocking" pressure oscillations when attempting high load HCCI combustion (Gray and Ryan, 1997; Christensen *et al*., 1997; Oakley *et al*., 2001). These characteristics make HCCI combustion well suited to improve the low to moderate load operation of internal combustion engines.

HCCI combustion is achieved by controlling temperature, pressure and composition of the air/fuel mixture. This can be done by controlling the parameters such as EGR or residual rate, air fuel ratio, Compression Ratio (CR), inlet mixture temperature, inlet manifold Figure

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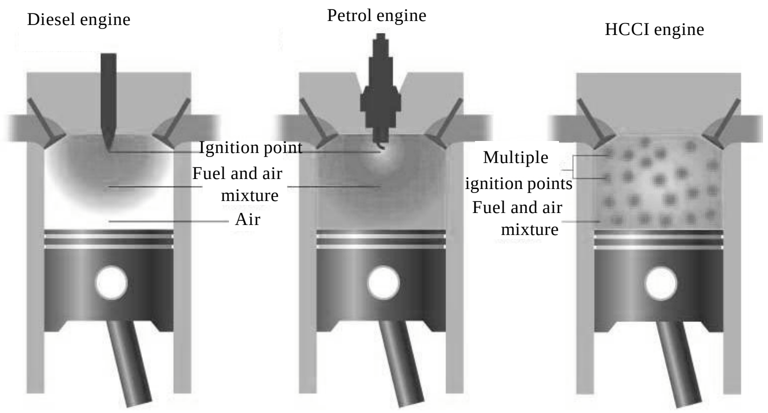

Fig. 1: Comparison between diesel, petrol and HCCI engines operation

pressure, fuel properties (or fuel blends), injection timing and coolant temperature. There is no direct control over the ignition timing as in SI and CI engines.

HCCI combustion when applied with gasoline fuel, it will offer an improvement in fuel economy and dramatic reduction in NOx emission compared to the spark ignition operated Zhao (2007). There are several approaches to achieve HCCI with gasoline fuel and the most obvious approach to achieve HCCI in a 4 stroke engine is by intake charge heating Najt and Foster (1983). In this study, the high intake air temperature was used to initiate HCCI combustion. Another means is to increase the CR to the point of required temperature and pressure for auto-ignition to achieve mainly through compression (Cristensen *et al*., 1999). Variation of fuel blend also been used by Olsson and Johansson (Olsson *et al*., 2001) to achieve HCCI combustion. This method used together with supercharging and intake air heating with the combination of isooctane and heptane to achieve HCCI combustion over a large speed and load range. Similar approach have been done by blending DME into methane to extend the HCCI operation and reduce emissions (Kaimai *et al*., 1999).

The most practical approach to achieve CAI combustion in gasoline engine is through the use of large amounts of burned gases by trapping them within the cylinder (Lavy *et al*., 2000; Law *et al*., 2001) or through internal Fig. 1: Comparison between diesel, petrol and HCCI engines operation recirculation (Li *et al*., 2001; Koopmans and Denbratt, 2001; Kahaaina *et al*., 2001; Fuerhapter *et al*., 2003). Their thermal energy will heat the charge to reach auto-ignition temperature and help to control the heat release rate. The advantage of this approach is that it can operate at a standard CR without the need of external heating. The method of intake air heating is used in this project to achieve HCCI combustion.

Table 1: Single cylinder research engine specification

Specification	Values
Displacement volume	399.25 cm^3
Cylinder bore	76 mm
Cylinder stroke	88 mm
Compression ratio	14
Exhaust valve closed	ATDC 10°
Exhaust valve open	BBDC 45°
Inlet valve open	BTDC 12°
Inlet valve closed	ABDC 48°
Dynamometer eddy current	maximum of 50 Nm
ECU Orbital Inc	

Engine setup: This experiment was performed using the Single Cylinder Research Engine available in the university, which was originally designed with CNG-DI system. This engine has CR 14 and operates on CNG-DI spark ignition. For gasoline SI combustion, the CR 14 is high and will result in knocking. The engine specification are summarize in Table 1. This engine was modified at the air intake manifold to operates on the gasoline HCCI.

CNG direct injection system: CNG-DI system will be operated as the existing engine setup and controls by the Engine Control Unit. CNG injects at various injection timing and amount to control the combustion of the engine. Stratified charge used to create a stratification effects in late injection timing (80 BTDC) where the ultra lean operation are possible.

Gasoline injection and dual fuel system: To operate the engine in dual fuel mode, a manifold injection system is added to the existing engine. The gasoline injection system consists of a intake manifold pipe, fuel pump, fuel rail, fuel pressure regulator and an injector. The fuel is injected into the intake manifold at a constant pressure

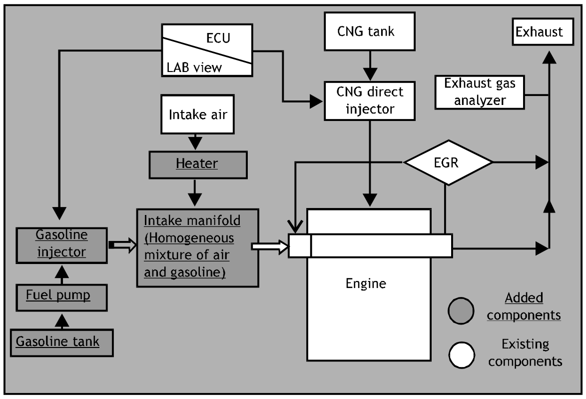

Fig. 2: Engine setup

of 3 bar. The injector is controlled by an injector driver through a LABVIEW program.

The intake air system includes an electrical air heater of 2.4 kW to control the air intake temperature. The power consumption of the heater will not be counted in the overall engine performance produce by the engine. Gasoline is injected after the heater to create a gasoline homogeneous charge. The dual fuel systems consist of controlling gasoline HCCI and CNG-DI separately. Figure 2 shows the experimental setup of dual fuel HCCI-DI engine modification

HCCI and SI operation

HCCI combustion of gasoline: As gasoline has high octane number (RON 92) and high auto ignition temperature, gasoline with ambient air intake and 14 CR is not sufficient to perform combustion. Therefore, intake air heater is added and combustion could achieve at 300°C charge temperature in homogeneous form. The gasoline combustion has been studied and looks into the range of air fuel ratios possible.

HCCI combustion of gasoline with CNG DI: The second stage is to operate the engine with addition of CNG direct injection. The leanest possible and stable gasoline HCCI operating range is selected for operation with CNG direct injection. CNG will be combusted by the heat liberated by the combustion of homogeneous gasoline. The amount of CNG supply is added to increase the load to the maximum possible. The CNG-DI combustion with HCCI gasoline at 2100 rpm is analyzed with possible torque limits.

Combustion of lean CNG DI: This engine is designed for CNG-DI operation and it is stable for lean stratified CNG-DI combustion. The combustion of CNG-DI at low load needs to operate in a stratified charge to get stable operation (below 10% Coefficient of Variation). Various amount of lean CNG is injected at 2100 rpm to determine the limits of CNG combustion possible. Table 2 shows the different between HCCI and SI operation mode.

Table 2: HCCI vs. SI Mode

	HCCI	SI
Ignition	-	On
Gasoline injection	On	-
CNG-injection	On	On
Throttle pos	WOT	WOT
Heater	On	-

RESULTS AND DISCUSSION

Heat release rate: The fundamental differences between SI and HCCI operation are illustrated in Fig. 3 and in Table 2. Figure 3 shows average Heat Release Rate (HRR) for SI and dual fuel HCCI operation at 2100 rpm and 6 Nm brake Torque.

Table 3 compares the engine operating parameters and emissions for these two cases. It can be noted that the HCCI heat release is higher compare with SI. At equal power output, the engine operates about the same lambda of HCCI mode and in SI mode (Lambda of 2.24 and 2.3, respectively), but yields higher exhaust gas temperatures (371 and 245 °C, respectively). The improvement in NOx is much better in HCCI than SI mode (252 and 485 ppm).

One of the fundamental challenges associated with practical use of HCCI combustion in reciprocating engines involves the control of combustion phasing relative to the engine cycle Stanglmaier and Roberts (1999). It is well documented that, holding the engine speed and other parameters constant, HCCI combustion occurs earlier in the cycle as the air/fuel mixture is enriched as CNG amount increase. This behavior is illustrated in Fig. 4 for SI and Fig. 5 for dual fuel HCCI. Heat Release Rate of HCCI is higher compare to SI due to more efficient combustion.

Pressure comparison: Figure 8 and 9 shows that the pressure rises comparison of HCCI and SI do not make much different in the maximum load. HCCI pressure rise is narrower and SI is broader. This is due to the rapid combustion in HCCI mode. Producing a 4 Nm in SI mode, the pressure rise very high as the engine is not stable and show by the COV that is more than 10%. HCCI is more stable then SI at low loads.

Mass fraction burn: The operation of HCCI gives a rapid mass fraction burn compare to SI. HCCI burns the fuel throughout cylinder in homogeneous form rapidly. The mass fraction burn is more complete (Fig. 6 and 7).

Table 3: Details of HCCI vs. SI operation

	Dual fuel HCCI	CNG-DI SI
Speed (rpm)	2100	2100
Torque (Nm)	6.3	6
IMEP (bar)	5.203282	3.68885
Natural gas flow rate g^{-1}	0.0315	0.166
Gasoline flow rate g^{-1}	0.102053	-
Ave. Exhaust temp. (°C)	371	245
Lambda (approx.)	2.24	2.3
HC (ppm)	635.1325	7213.24
CO (ppm)	1060.01	322.99
NOx (ppm)	252.695	485.5283

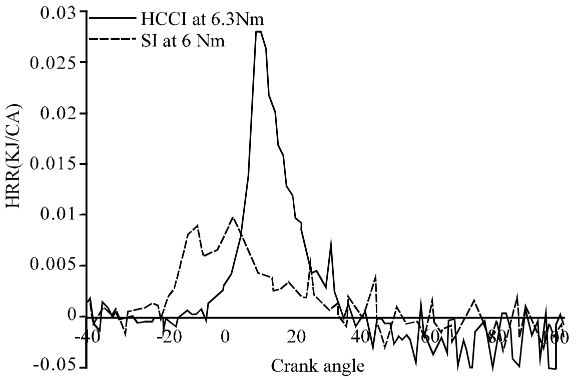

Fig. 3: Heat release rate vs. crank angle degree comparing HCCI and SI at 2100 rpm

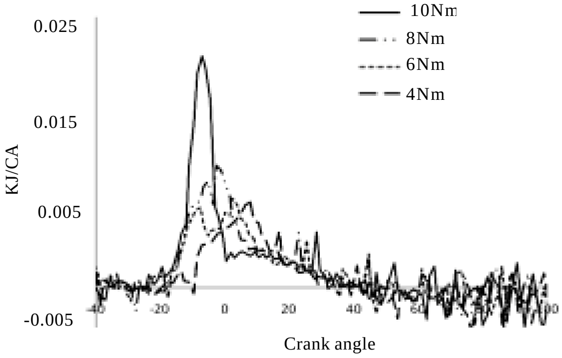

Fig. 4: Heat release rate vs. crank angle degree of SI at 2100 rpm

Energy consumption: HCCI combustion at low engine loads has been proposed in this paper as a method for improving the fuel efficiency of natural gas engines. Figure 10 shows the approximate Indicated Specific Energy Consumption (ISEC) of the engine in HCCI and SI mode as a function of IMEP. This plot illustrates that 20-25% improvement in energy consumption can be obtained in the load range between 4 and 5 bar IMEP.

Exhaust emission: The concentrations of unburned and partially-burned hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx) in the exhaust stream were measured during HCCI and SI operation and are shown in Table 2. It should be noted that the ignition timing and equivalence ratio during SI operation were not fully optimized with regards to emissions.

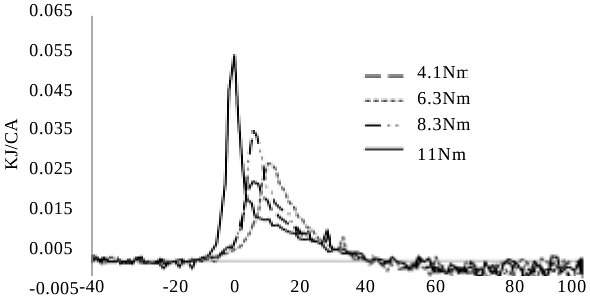

Fig. 5: Heat Release Rate vs. Crank Angle Degree of HCCI at 2100 rpm

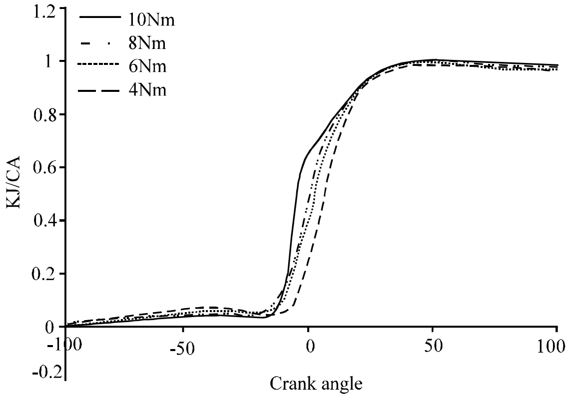

Fig. 6: Mass Fraction Burn vs. Crank Angle Degree of SI at 2100 rpm

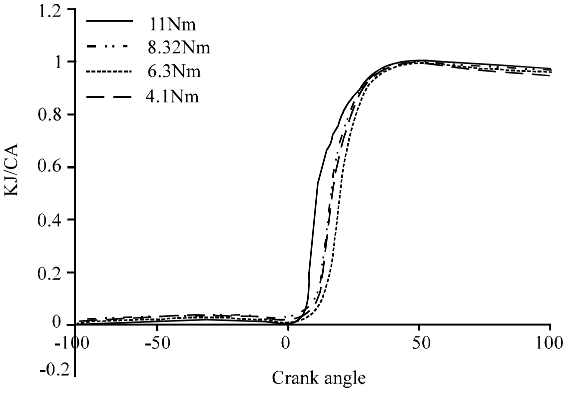

Fig. 7: Mass Fraction Burn vs. Crank Angle Degree of HCCI at 2100 rpm

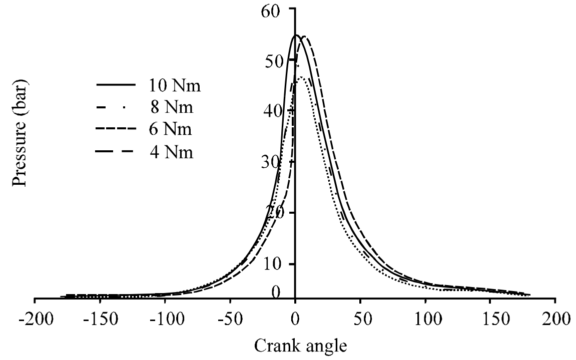

Fig. 8: Average cylinder pressure vs. crank angle of SI low load

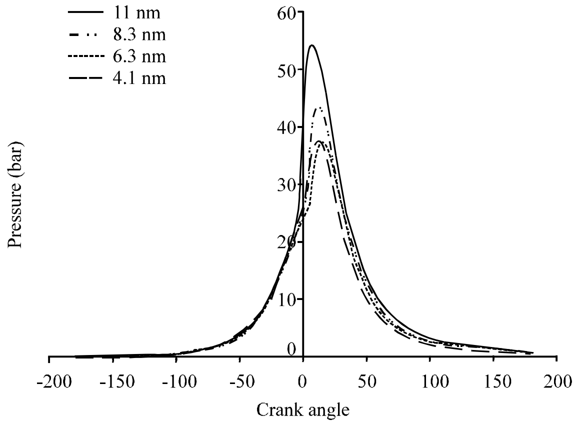

Fig. 9: Average cylinder pressure vs. crank angle of HCCI low load

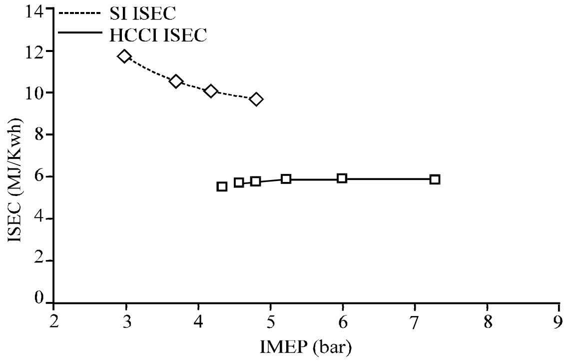

Fig. 10: ISFC vs. IMEP of SI and HCCI at low load, Indicated specific energy consumption ISEC (MJ/Kwh)

At this particular condition, HCCI operation of the engine resulted in lower HC concentration than in SI mode as in Fig. 11. The exhaust concentration of CO was about five times higher in HCCI mode than in SI mode in low load; it increases as the load increases. At a point of 10 Nm, the CO emission seems to be the same with SI operation. CO shows incomplete combustion and

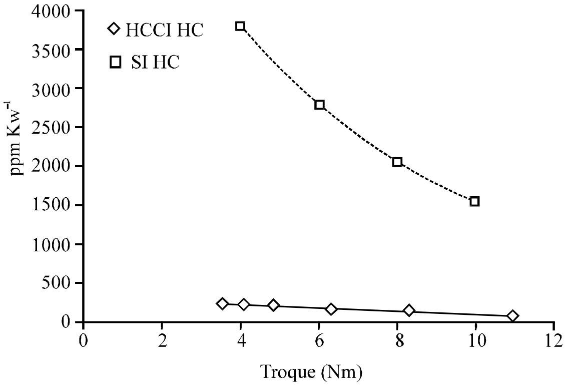

Fig. 11: Exhaust concentration of HC of HCCI and SI at different load

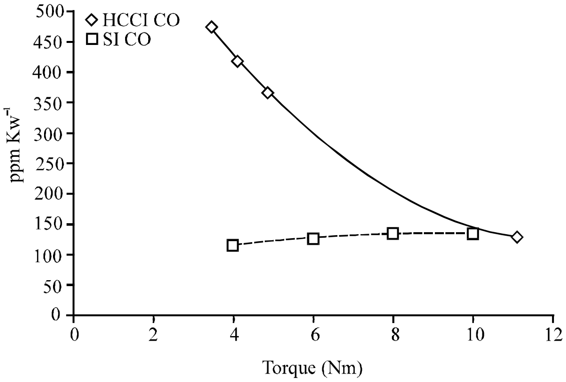

Fig. 12: Exhaust concentration of CO of HCCI and SI at different load

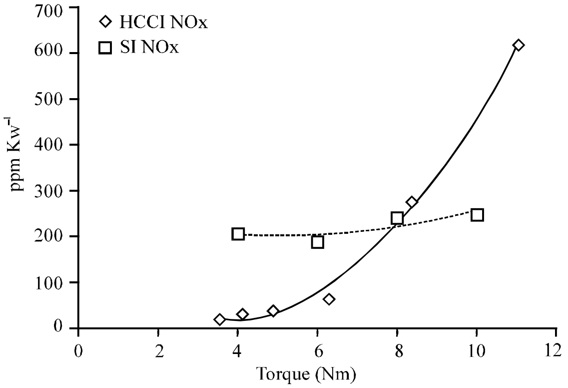

Fig. 13: Exhaust concentration of NOx of HCCI and SI at different load

the operation at more than 10 Nm, HCCI operation is not stable Fig. 12.

The most dramatic difference in the emissions, however, is that the NOx concentration was double lower in HCCI mode than in SI mode. At around 8 Nm, the emission seems to be the same and increases very high due to the knocking phenomenon in HCCI Fig. 13.

CONCLUSION

Based on the findings in this project, it can be concluded that HCCI is more suitable to be operated in low load and SI is better in higher load operation. HCCI operation at low engine loads appears to be very attractive for improving the thermal efficiency and reducing NOx emissions compared to spark-ignited natural gas engines. There is a trade off between the load limits of HCCI and NOx emissions become more than SI combustion beyond certain loads.

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