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EXPERIMENTAL COMPARISON OF GCI AND DIESEL COMBUSTION IN A MEDIUM-DUTY OPPOSED-PISTON ENGINE

Reed Hanson
Achates Power
San Diego, CA, USA

Ashwin Salvi
Achates Power
San Diego, CA, USA

Fabien Redon
Achates Power
San Diego, CA, USA

Gerhard Regner
Achates Power
San Diego, CA, USA

ABSTRACT

The Achates Power Inc. (API) Opposed Piston (OP) Engine architecture provides fundamental advantages that increase thermal efficiency over current poppet valve 4 stroke engines. In this paper, combustion performance of diesel and gasoline compression ignition (GCI) combustion in a medium duty, OP engine are shown.

By using GCI, NO_x and/or soot reductions can be seen compared to diesel combustion at similar or increased thermal efficiencies. The results also show that high combustion efficiency can be achieved with GCI combustion with acceptable noise and stability over the same load range as diesel combustion in an OP engine.

INTRODUCTION

Opposed-piston, two-stroke engines have been around since the 1800's and have subsequently been developed for a wide variety of applications ranging from aircraft to light and heavy-duty vehicles and prime movers for power generation [1-7].

Initially developed for manufacturability and high-power density, the opposed-piston (OP) two stroke engine has demonstrated superior fuel efficiency compared to its four-stroke counterparts. The main benefit for the OP engine is the lower heat transfer losses due to the reduced surface area to volume ratio from the elimination of the cylinder head.

This work was done in support of developing the combustion system recipe for a light-duty (LD) OP engine that is part of a contract from the U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E). The main aspect to the project is to use GCI combustion in a light duty, compression ignition engine.

GCI is a low temperature combustion mode that uses compression ignition of gasoline instead of spark ignition. By using compression ignition, higher compression ratios can be used along with lean air-fuel ratio operation, allowing for large increases in thermal efficiency over conventional spark ignition engines. GCI also offers high thermal efficiencies and low emissions due to the lower combustion temperatures. Research on GCI combustion has been an ongoing research topic over the last decade in many research laboratories and universities all over the world [8-15].

GCI is being researched because it is possible to simultaneously reduce soot and NO_x emissions while maintaining or even improving indicated thermal efficiency (ITE) over current engines. Conversely, HC and CO emissions are increased compared to current diesel engines but are on par with spark ignition engines.

Low-load operation is challenging for GCI due to low cylinder gas temperatures, resulting in poor autoignition characteristics of the low reactivity fuel. Inversely, high-load GCI operation suffers from increased combustion noise due to high cylinder pressure rise rates from the rapid autoignition of the fuel.

Four stroke engines attempt to improve light load GCI combustion by using rebreathing strategies with variable cam phasing to increase the internal exhaust residual fraction. They also increase intake pressures with a supercharger to improve the pressure dependent autoignition characteristics of gasoline. The OP engine does not need to do either because its exhaust residual fraction is larger than a four stroke engine and is controlled by the pressure differential across the intake and exhaust manifolds. The higher residual fraction increases gas temperatures at low loads for better ignitability of low cetane fuels such gasoline. Additionally, high-load OP GCI operation can be easier as the peak BMEP is lower than conventional four stroke engines due to having two power strokes per cycle instead of one to reach the same shaft torque.

NOMENCLATURE

AFR	Air Fuel Ratio
aMV	After Minimum Volume
ANL	Argonne National Laboratory
API	Achates Power Incorporated
ARPA-E	Advanced Research Projects Agency – Energy
BMEP	Brake Mean Effective Pressure
BTE	Brake Thermal Efficiency
CDC	Conventional Diesel Combustion
CFD	Computational Fluid Dynamics
CN	Cetane Number
CNL	Combustion Noise Level
CO	Carbon Monoxide
CR	Compression Ratio
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
FSN	Filter Smoke Number
FTP	Federal Test Procedure
GCI	Gasoline Compression Ignition
HC	Hydrocarbon
HRR	Heat Release Rate
IMEP	Indicated Mean Effective Pressure
ITE	Indicated Thermal Efficiency
LD	Light Duty
MCE	Multi Cylinder Engine
MD	Medium Duty
MPRR	Maximum Pressure Rise Rate
NOx	Nitrogen Oxides
NVH	Noise Vibration Harshness
OP	Opposed Piston
OP GCI	Opposed Piston Gasoline Compression Ignition
PCP	Peak Cylinder Pressure
SCE	Single Cylinder Engine
SCR	Selective Catalyst Reduction
SOI	Start of Injection

EXPERIMENTAL SETUP

To investigate OP GCI combustion in preparation for the LD OP engine, the 1.64L API single cylinder engine (SCE) was used. This SCE has been well studied and is used for combustion and power cylinder development testing [6-7]. The SCE specifications are shown in Table 1.

Table 1 API SCE Specifications

Number cylinders	#	1
Bore	mm	98.4
Stroke	mm	215.9
Stroke/Bore	-	2.2
Swept volume	L	1.64
Trapped Compression Ratio	-	18.5

One thing to note is the high CR used, which is higher than is typically used for GCI or diesel. The CR was chosen because test results of different CR in the OP engine showed that 18.5 was optimal to increase the gas temperature and pressure for improved ignition of the low reactivity gasoline fuel. The CR was driven by the fuel choice rather than the engine architecture. This CR was used with both diesel and gasoline fuels. A high swirl liner was also installed to mitigate soot emissions.

The SCE is connected to an AC dyno for load control. The soot emissions are measured by an AVL 415S smoke meter. Gaseous emissions are measured by both an FTIR for NO_x and a five-gas bench for the rest of the gases. Combustion noise was measured using an AVL noise meter.

High speed combustion data were processed using an in house LabView code with 0.25 deg resolution crankshaft encoders on each crankshaft. Low speed data were acquired with a Cyflex system.

Due to the prototype nature of the SCE, the EGR, air and engine coolant are provided by external carts that can give the same conditions as a full multi-cylinder engine (MCE). Details of lab setup can be seen in [6-7].

The gasoline fuel flow rate is measured by a system which has a Coriolis type flow meter. Diesel fuel was measured by a separate fuel system, also with a Coriolis type meter. The airflow was measured by a Coriolis type flow meter. The fuel injection system is controlled by a Pi Innovo Open ECU. The current fuel injection system is a common rail with 1800 bar maximum fuel pressure. The injectors used were Delphi prototype injectors, with the engine having two injectors per cylinder. Details on the injectors are confidential.

The gasoline fuel used in the project is a certification gasoline based on US Tier3 commercial fuel specifications. This fuel is an E10 blend with 87 AKI ((RON+MON)/2) and low sulfur. For gasoline use, a lubricity additive is added to the fuel and there is a max pressure limit of 1800 bar for component durability.

Diesel fuel is an off-road California specification fuel with 53 CN. Fuel specifications are shown in Table 2 and Table 3, respectively.

Table 2 Gasoline Fuel Specifications

Fuel		Gasoline
Ethanol	%vol	10
RON	-	91
MON	-	83
AKI	-	87

Table 3 Diesel Fuel Specifications

Fuel		Diesel
Cetane number	CN	53.2

RESULTS

Experiments for this study were originally designed to cover the 13 mode SET, which has test points at 1400, 1800 and 2200 rpm, with loads from 25-100%. The OP GCI engine was operated over these modes, but the peak load was limited to 75% of what is capable in this engine to keep PCP below 200 bar. The high CR raises the PCP at these high loads to over 200 bar at the intake pressures normally used in the MCE, so future work is needed to lower the intake pressures or to change hardware so that the engine can handle PCP above 200 bar.

Combustion performance across speeds was similar, so only the peak torque speed results were chosen for this paper for brevity. Additionally, since loads below 25% were not a part of the original study, a 1 bar, 1300 rpm point from a previous low load study was selected to highlight the engine performance from low loads to high loads. The selected test points can be seen in Figure 1.

Additional work is also being done which focuses on speed and loads typical of the US FTP75 certification test. The SCE was also previously operated over these conditions, but the results are not included in the paper. Similar results on the light-duty OP engine testing and CFD results are given in [16,17].

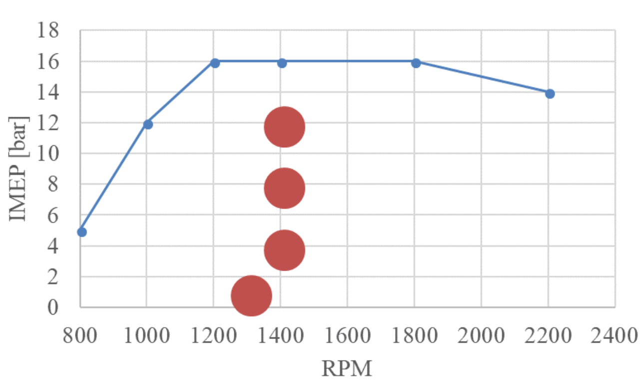

Figure 1 GCI and diesel SCE test points

Boundary conditions

Boundary conditions for the GCI and diesel tests were derived by testing on a 4.9L MCE version of the SCE. The goals for the GCI testing were to reach the max ITE within noise and NO_x targets. Noise targets from the ACEC team were chosen and the NO_x limit was chosen from a typical MD engine-out level for use with an SCR. For the GCI tests, intake temperature, rail pressure and intake pressure were kept the same for both fuels. AFR and EGR were similar between fuels, but was allowed to float within ranges allowed by the MCE to hit the noise target and NO_x target of 1-4 g/kWh. AFR in the paper is defined as the delivered airflow divided by the delivered fuel flow. Table 4 shows the EGR, AFR, rail pressure, and intake pressures. Intake temperature was the same for both fuels at 45 °C.

Table 4 Boundary Conditions

GCI	IMEP	1 bar	4 bar	8 bar	12 bar
Speed	RPM	1300	1400	1400	1400
Intake Pressure	(bar)	1.12	1.33	1.91	2.30
Fuel Rail Pressure	(bar)	326	748	1001	1303
EGR Rate	(%)	35.2	28.0	26.5	22.6
AFR	(-)	26.7	29.2	29.7	26.7
Diesel					
Speed	RPM	1300	1400	1400	1400
Intake Pressure	(bar)	1.12	1.33	1.90	2.32
Fuel Rail Pressure	(bar)	602	750	1000	1300
EGR Rate	(%)	24.8	37.0	28.2	25.3
AFR	(-)	27.9	27.7	29.6	25.7

Injection

Injection parameters are the main differences between diesel and GCI combustion in the OP engine. GCI used a pilot/main strategy at all conditions where diesel only used one at 1 and 4 bar IMEP. The diesel injection strategy was used from a previous calibration, while the GCI injection stragety was driven by previous OP GCI test results (that are not discussed) and research into the literature [8-15, 18, 19]. The OP GCI strategy followed four stroke GCI strategies, which typically have multiple injections with high pilot fractions and earlier SOI timings. However, since there is no intake stroke in a two stroke engine, the OP GCI injection strategy had to use later SOI timings and lower pilot fractions than are typically used in four stroke engines.

OP GCI results have a higher pilot mass fraction with a similar main SOI timing as compared to diesel operation. Also like diesel combustion, GCI was able to control combustion phasing at all loads by the main SOI timing. Injection parameters are given in Table 5.

Table 5 Injection Parameters

GCI	IMEP	1 bar	4 bar	8 bar	12 bar
Main SOI	Deg aMV	-12	-7	-8	-8
Pilot SOI	Deg aMV	-44	-45	-46	-46
Inj quantity	mg	10.9	35.8	65.4	95.9
Pilot mass frac.	-	0.64	0.49	0.30	0.16

Diesel	IMEP	1 bar	4 bar	8 bar	12 bar
Main SOI	Deg aMV	-9.5	-5	-8	-9
Pilot SOI	Deg aMV	-15	-8	-	-
Inj quantity	mg	11.4	32.5	63.3	92.2
Pilot mass frac.	-	0.17	0.06	0	0

Combustion Results

Combustion results from the GCI and diesel combustion tests showed to be more similar than initially expected. OP GCI was closer to mixing controlled diesel combustion than is usually seen in four stroke GCI results [8-15]. OP GCI was much less premixed and dilute with more mixing controlled combustion at high loads. This was by choice to increase combustion efficiency and phasing control with boundary conditions that more closely represent operation with real turbomachinery. Figure 2 through Figure 5 show the pressure and HRR for both diesel and GCI.

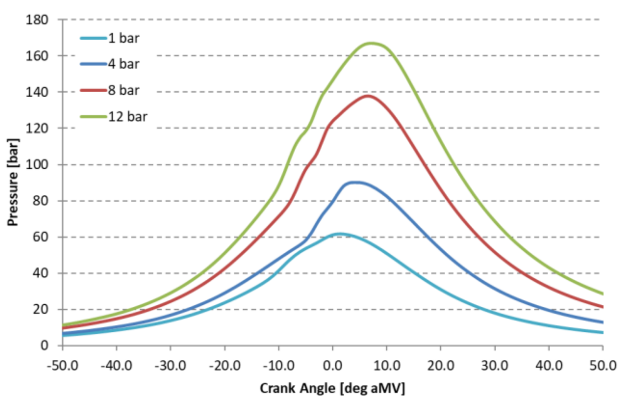

Figure 2 GCI cylinder pressure traces

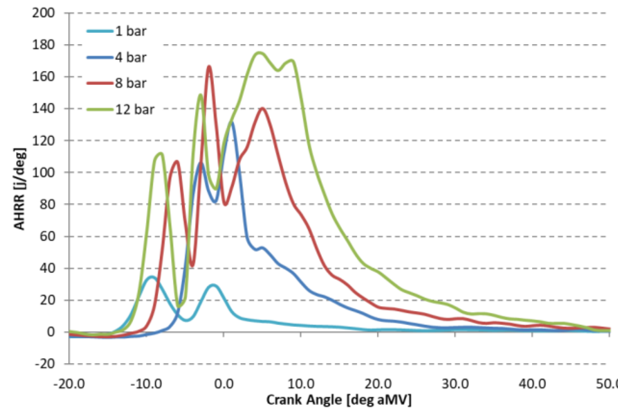

Figure 3 GCI HRR traces

1 bar IMEP operation for both fuels was similar in that a pilot injection was used, resulting in a double peak HRR. This gave similar burn durations, but GCI had an earlier CA50, due to the higher mass fraction of the pilot injection.

At 4 bar IMEP, more typical GCI results were seen where the combustion was much shorter, with a higher max HRR. A high premixed fraction could be achieved with GCI while still meeting noise targets. With a larger premixed fraction, more of the air/fuel charge is at a lower equivalence ratio and temperature, reducing NO_x emissions. With lower NO_x formed by combustion, less EGR could be used to meet the NO_x emissions targets. The lower equivalence ratios also gave a significant soot reduction.

As load increased to 8 bar IMEP, GCI combustion started to behave more like diesel combustion. While there is still a pilot injection, the pilot mass fraction is starting to reduce and continues to reduce with load. This can be seen in the HRR where there is a first pilot ignition around -10 deg aMV, but then a typical diffusion burn with a premixed spike is seen.

Then at 12 bar IMEP, GCI has become full diffusion combustion as the pilot fraction is only 16%, which also shows that most of the fuel is injected late in the cycle. There is a clear premixed spike and diffusion sections. Note that both GCI and diesel reach a similar max HRR during the diffusion section. Using this injection strategy, full load (16 bar IMEP) OP GCI opertion will likely have little to no pilot injection and have a HRR shape that is same as diesel opertion. Future testing will be done to test this hypothesis.

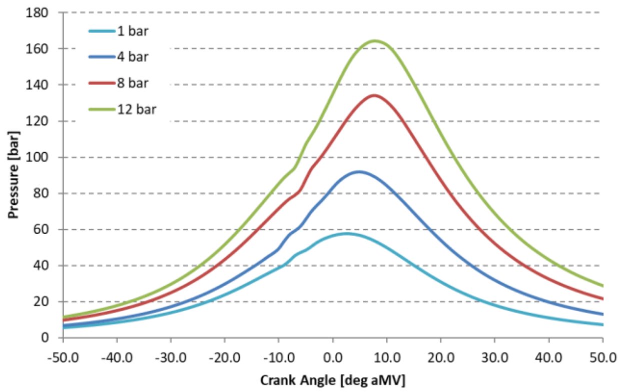

Figure 4 Diesel cylinder pressure traces

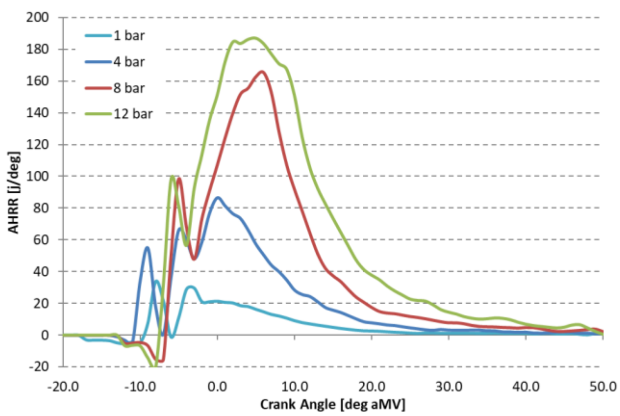

Figure 5 Diesel HRR traces

These specific combustion differences can also be seen Figure 6 to Figure 9. It can be seen that GCI has slightly more advanced and louder combustion than diesel, but was still lower than the ACEC noise guidelines. Since combustion noise is an adjustable parameter, GCI was able to have earlier phasing due to the reduced NO_x emissions and EGR rates while meeting the combustion noise targets.

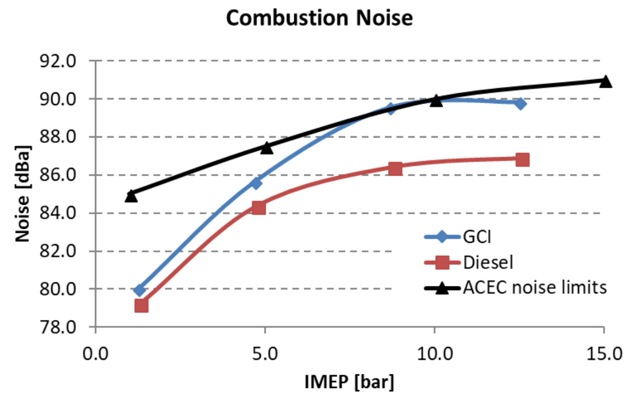

Figure 6 Combustion noise

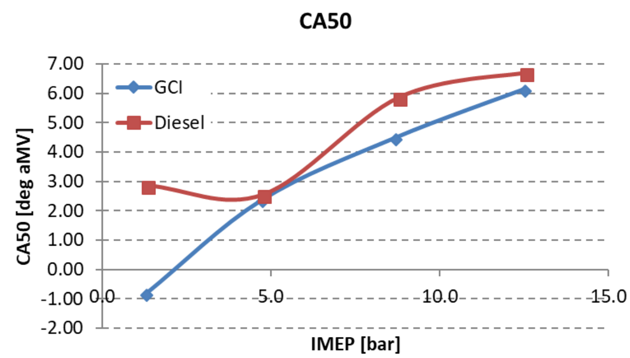

Figure 7 CA50

Diesel combustion was phased later to reduce NO_x with higher EGR rates. CA50 could be advanced and still meet noise limits, but would need more EGR, increasing pumping losses. GCI met noise targets with around 1-2 bar/deg and 2-3 dB(A) more than diesel combustion, which is typical of GCI combustion. If desired, GCI CA50 could be delayed with main SOI timing and pilot mass fraction.

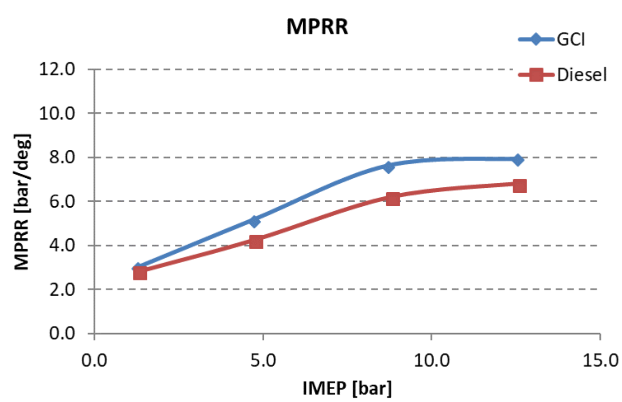

Figure 8 MPRR

As shown in Figure 9, GCI and diesel had similar CA10-90 burn durations, with GCI having faster combustion at 4 bar, where it was more premixed and the max HRR was higher. GCI had longer combustion at higher loads due to the increased pilot mass fraction heat release before the main injection heat release. Combustion stability was also acceptable for both fuels, ranging from 3% at 1 bar IMEP to 1% CoV of IMEP at 12 bar IMEP.

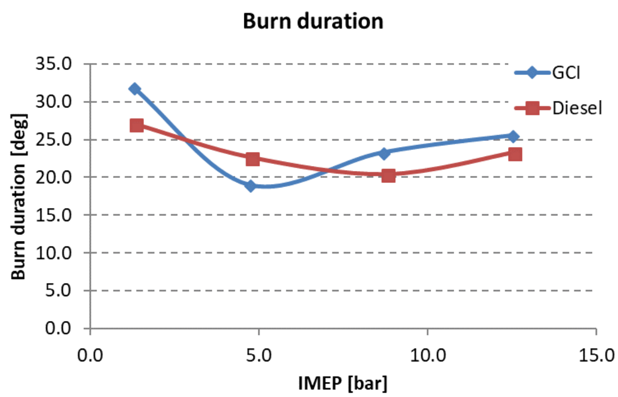

Figure 9 Burn duration

Efficiency

In two stroke engines, there is no pumping loop, thus only gross indicated thermal efficiency is presented. As shown in Figure 10, the ITE increases with load and was >50% above 4 bar IMEP. The error bars are from an uncertainty analysis with a 95% confidence interval.

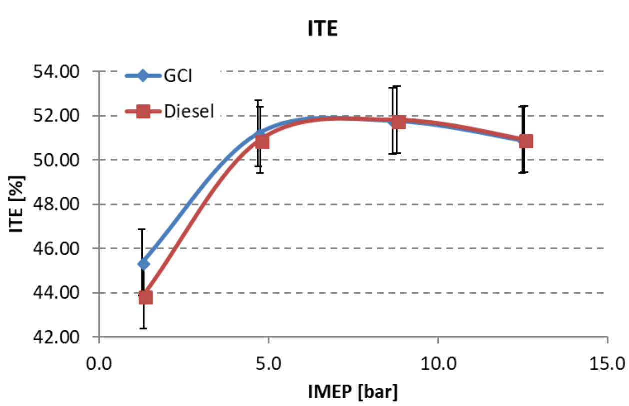

Figure 10 Indicated thermal efficiency

High ITE from the OP engine is shown to be from the low surface area/volume ratio, lean operation and high CR [6]. An interesting result is that ITE was similar between gasoline and diesel operation, with GCI having a slight advantage at light loads. High load GCI and diesel lose ITE due to increased burn durations, combustion noise and PCP limitations.

Emissions

Emissions from GCI and diesel are also examined, as shown from Figure 11 to Figure 14. For the study, NO_x emissions were targeted to be the same for both fuels to examine differences in the fuel injection calibraiton. As can be seen Table 4, less EGR was needed for GCI to match the NO_x of the diesel results, except at 1 bar, where GCI NO_x emissions were lower and EGR was higher.

As typical with GCI combustion, soot was reduced from the increased amount of premixed fuel. This is the reason for the different soot/NOx trade off seen with gasoline compared to diesel. At lower loads, with gasoline, more of the fuel is injected earlier, giving more time for premixing, thus avoiding the soot formation regions, but the temperatures are still high enough to form some NOx and oxidize the HC and CO. Then at high load, the pilot mass fraction reduces, with combustion becoming more similar between the fuels, giving similar NO_x and soot emissions. With the different soot/NO_x tradeoff of using gasoline, the engine has greater flexibility in different engine calibrations for different applications. It could be possible to have much lower NO_x emissions for the same soot emissions as diesel operation or even a higher NO_x, low soot calibration. This could be an enabler to meet future ultra-low NO_x emissions standards or even reduce aftertreatment costs. GCI operation could also have higher real-world fuel economy because there will be less fuel used from less frequent DPF regeneration events.

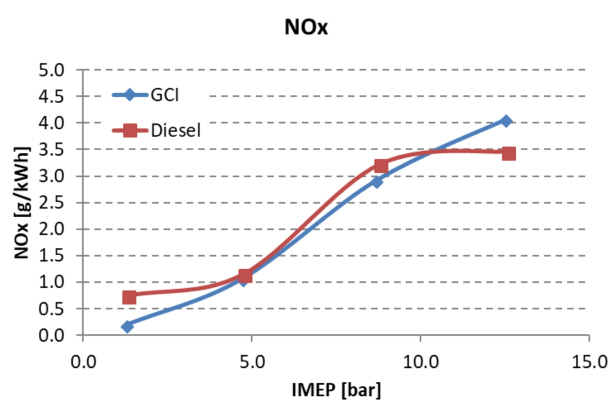

Figure 11 NOx emissions

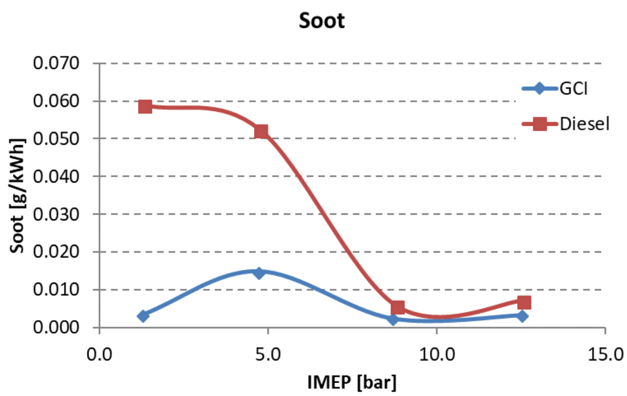

Figure 12 Soot emissions

As previously mentioned, GCI had increased HC and CO emissions over diesel combustion, as shown in Figure 13 and Figure 14. This is not unexpected, as four stroke GCI shows the same trends [8-15, 18, 19]. Injecting fuel earlier in the cycle gives more HC and CO emissions due to fuel sprays impinging on the liner and unburned fuel transporting to the top land crevice volumes. However, it must be noted that OP GCI HC and CO emissions are still much lower than are typically seen with GCI combustion in four stroke engines. Part of the reduction in HC and CO compared to four stroke GCI is due to higher gas temperatures from the elevated CR and adjustable residual fraction available in the OP engine. Another part is from the lower pilot mass fractions and reduced EGR and excess air. The final part is the later SOI timings, which could limit spray-wall interactions and fuel becoming trapped in the crevices [8-15, 18, 19].

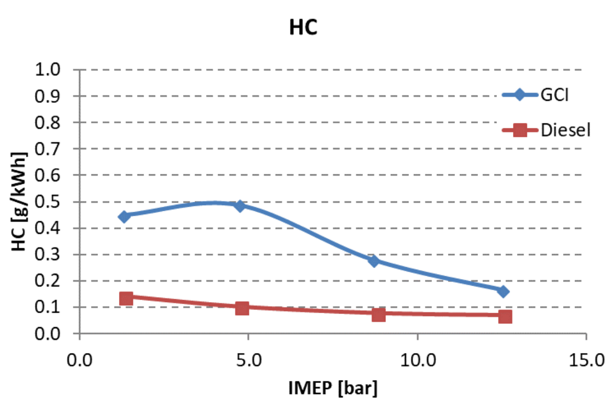

Figure 13 HC emissions

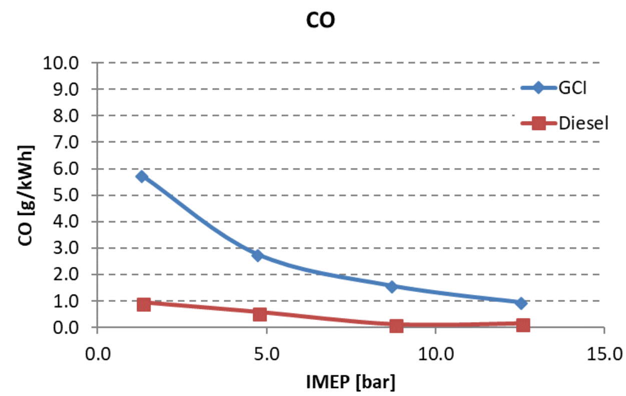

Figure 14 CO emissions

Following the HC and CO emissions, the combustion efficiency was very high and was greater than 98% at all selected loads and is shown in Figure 15. This is much higher than typical four stroke GCI results and even approaches diesel combustion at high loads [8,19].

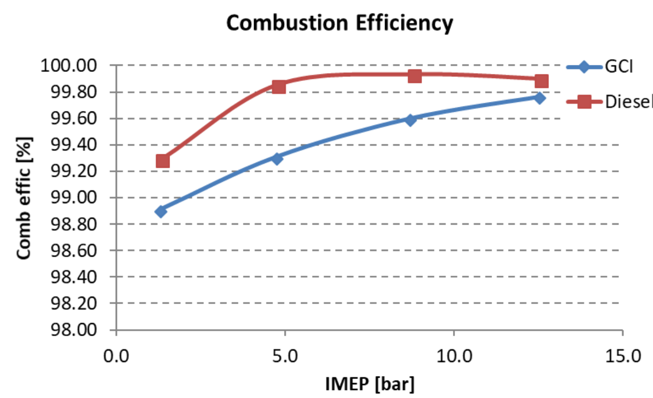

Figure 15 Combustion efficiency

CONCLUSIONS

GCI and diesel combustion and emissions performance were compared in the same single cylinder OP engine with similar boundary conditions. With matched NO_x emissions, some conclusions about the differences in GCI and diesel combustion can be shown:

1. GCI could be operated over the same load range as with diesel fuel.
2. GCI was able to use lower EGR rates to reach the same NO_x emissions as diesel fuel.
3. GCI offered similar ITE compared to diesel operation.
4. GCI had a different NO_x vs. soot trade off than diesel operation. With the same NO_x emissions, GCI had up to 3-10 times less soot.
5. GCI had increased HC and CO emissions from the larger and earlier pilot injection compared to diesel combustion. GCI had >98% combustion efficiency at the selected operating points.

6. GCI was calibrated to have slightly higher combustion noise than diesel operation due to earlier CA50 while still meeting the combustion noise targets.

Overall, the OP engine was shown to be fuel flexible and capable of high thermal efficiency and reasonable emissions using either gasoline or diesel fuel.

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