

Gasoline Direct Injection Compression Ignition (GDCI) - Diesel-like Efficiency with Low CO2 Emissions

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ABSTRACT

A single-cylinder engine was used to study the potential of a high-efficiency combustion concept called gasoline direct-injection compression-ignition (GDCI). Low temperature combustion was achieved using multiple injections, intake boost, and moderate EGR to reduce engine-out NO_x and PM emissions engine for stringent emissions standards. This combustion strategy benefits from the relatively long ignition delay and high volatility of regular unleaded gasoline fuel.

Tests were conducted at 6 bar IMEP - 1500 rpm using various injection strategies with low-to-moderate injection pressure. Results showed that triple injection GDCI achieved about 8 percent greater indicated thermal efficiency and about 14 percent lower specific CO₂ emissions relative to diesel baseline tests on the same engine. Heat release rates and combustion noise could be controlled with a multiple-late injection strategy for controlled fuel-air stratification. Estimated heat losses were significantly reduced. GDCI has good potential for full-time operation over the US Federal drive cycle.

INTRODUCTION

Compression-ignited diesels have long been the most efficient internal combustion engines. However, diesel engines are challenged to meet future stringent NO_x and PM emissions regulations at acceptable cost. Kalghatgi demonstrated in both large bore [1,2] and small bore diesel engines [3] that if gasoline-like fuels are injected near but before TDC, both very low NO_x and PM emissions, and high efficiency, could be achieved. This combustion process may be described as “premixed enough” but not “fully mixed,” as

in homogeneous charge compression ignition (HCCI) engines.

Kalghatgi [4] showed that the higher resistance to autoignition for the gasoline fuels means these fuels have greater ignition delay than the diesel mid-distillate fuels. [Figure 1](#) shows octane number plotted against volatility for a range of fuel types [4]. During the injection and mixing processes, gasoline fuels have more time for fuel-air mixing. The higher volatility of gasoline also aids in the mixing process. This established that gasoline fuels including alcohols are better suited for partially premixed, low-temperature combustion processes.

Groups at the University of Wisconsin [5,6,7] and Lund University [8,9,10] have also tested gasoline fuels in diesel engines. They demonstrated [high-load](#) capability using gasoline and ethanol in both heavy-duty and light-duty diesel engines. Extensive computational studies were conducted by Ra and Reitz [7]. Predicted cylinder pressure, heat release, and emissions for gasoline injection were compared to those for diesel injection. Both single and double injection strategies with various injection timings were investigated to achieve minimum emissions. With this previous work, it is evident that operation of CI engines on gasoline fuels can greatly facilitate low NO_x and low smoke operation. These studies demonstrated good potential for high load operation beyond typical HCCI levels.

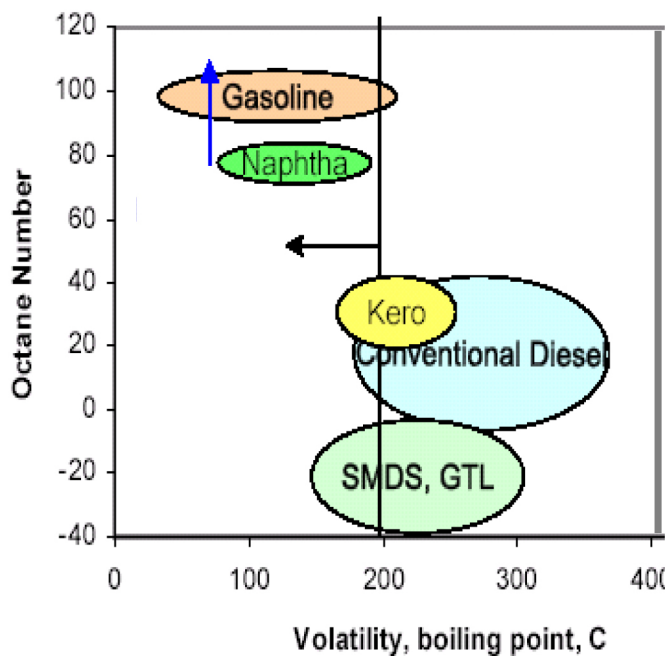


Figure 1. Octane number as a function of volatility for a range of fuel types from reference [4].

All of these prior studies have been conducted on production diesel engines with diesel fuel injection systems. Many issues remain related to light load operation, injection strategies and injection pressure requirements, control of pressure rise rates, combustion noise, high speed operation, and cold starting. Practical system implementation has not been demonstrated.

In the current work, the combustion process is referred to as Gasoline Direct Injection Compression Ignition (GDCI). Preliminary single-cylinder engine tests were performed at a medium speed and medium load condition. One objective is to achieve GDCI combustion using low injection pressures below the typical diesel range. A GDCI injection system is being developed for this purpose. Various injection strategies were tested and evaluated against preliminary emissions targets and noise constraints.

EXPERIMENTAL DESCRIPTION

The experiments performed in this study were performed on a Ricardo Hydra light-duty single-cylinder engine. A photograph of the engine is shown in [Figure 2](#); dimensions for the engine are listed in [Table 1](#). The engine configuration is four-valve, double-overhead cam with central injection. The aluminum cylinder head is rated at 200 bar peak cylinder pressure (PCP).

The engine is very flexible and parts can be easily interchanged. A removable injector sleeve enables testing of various injector types and sizes. Valve events may be changed by changing camshafts. Pistons and piston shapes

can also be changed and compression ratio adjusted via block shims. A port throttle on the rear intake port regulates the in-cylinder swirl ratio between 0.5 and 3.0.

The fuel used was regular unleaded RON91 gasoline representative of available pump fuel in the United States. The fuel contained no oxygenates. Fuel properties are shown in [Table 2](#).

The fuel injection system used was a Delphi developmental gasoline direct-injection system. Fuel pressure at the injector inlet was measured using a Kistler 4067C dynamic pressure transducer.

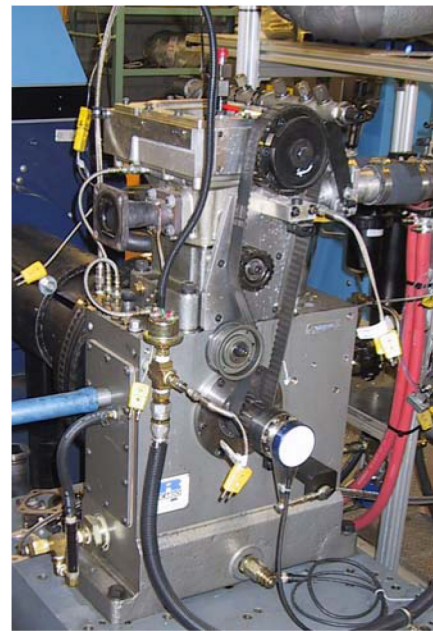


Figure 2. Single-cylinder Hydra engine.

Table 1. Specifications and dimensions of single-cylinder Hydra test engine.

Engine Type	4-valve Comp. Ignition
Bore × Stroke	84 × 90 mm
Displacement	499 cc
Compression Ratio	16.2 (adjustable)
Max. Cyl. Pressure	200 bar
Injection	Central mount – various injector types
Piston & Bowl	piston blanks & variants
DOHC Type II Valvetrain	Fixed cams (selectable)
Swirl ratio	Variable (0.5 ~ 3.0) PDA

A schematic diagram of the engine test setup is shown in Fig. 3. The intake and exhaust systems allowed simulated turbo-charged operation with wide range of intake and exhaust pressures. The intake air temperature was controlled using a 6 kW Chromalux air heater. EGR was controlled by a V-cut ball valve located between the exhaust and intake surge tanks. EGR was cooled by a water-cooled heat exchanger. Two 38 liter tanks were used as the intake and exhaust surge tanks in order to minimize pressure fluctuations and to mix the EGR well with the fresh intake air.

Air flow was controlled and measured with a Flow Systems FC-500 air system using a 7-nozzle sonic array. Fresh and dry air was supplied from the building compressed air system. Regulation of intake air to the engine was very good.

Fuel flow was measured with a high-precision Pierburg PLU103b fuel meter. The total error of this instrument as calibrated is 0.3 percent of reading down to 0.05 g/s fuel flow. This provided very accurate measurements of fuel flow to the engine even at idle conditions.

All emissions were measured on a wet basis using heated sampling systems with filters at 191 deg C. An AVL Sesam FTIR was used for carbon species, nitrogen species, and some hydrocarbon species. A Horiba Fast FID was used for total hydrocarbon emissions, and a Rosemount MLT-3 was used for exhaust oxygen and intake CO₂ emissions. An AVL 415S smoke meter was used to measure particulate emissions.

Table 2. Fuel properties for test gasoline.

Parameter	Value	Units
Density	0.7426	g/cc
H/C Ratio	1.871	atomic
O/C Ratio	0	atomic
Lower Heating Value	43.397	MJ/kg
Octane	86.65	
RON	90.6	
MON	82.7	
T0	33.8	C
T50	99.2	C
T100	209.2	C
Aromatics	26.1	vol%
Olefins	2.8	vol%
Saturates	70.9	vol%
Ethanol	0	vol%
Sulfur	5	ppm

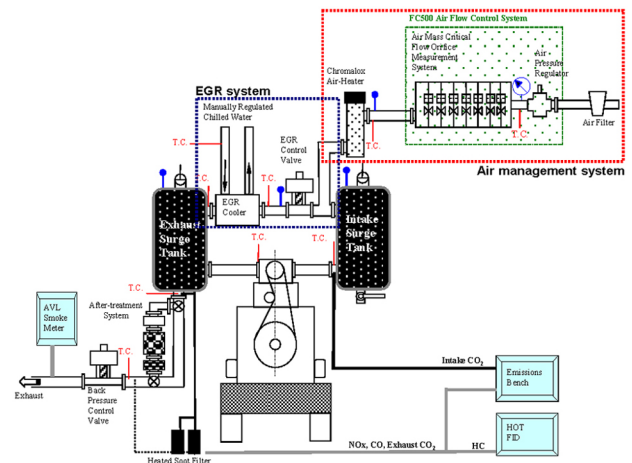


Figure 3. Schematic diagram of engine setup.

Cylinder pressure was measured with a flush-mounted Kistler 6125CU20 pressure transducer. A Kistler 2613B crankshaft encoder provided crank position data and was dynamically aligned with engine TDC using a Kistler 2629B TDC probe. Pressure data was sampled every 0.5 CAD.

A single-cylinder engine controller was developed with real-time heat release analysis capability. A schematic of the controller with sensors and actuators is shown in Figure 4. Both high-speed and low-speed data may be acquired by the system. The controller is based on National Instruments hardware and Labview software [11], and was built by Driven, Inc [12].

Residual mass concentration in the cylinder was measured by a Delphi Residual Estimator Tool (RET) [13, 14]. Figure 5 shows the RET. Inputs to the RET are cylinder pressure, average intake and exhaust port temperatures, and average intake and exhaust pressures.

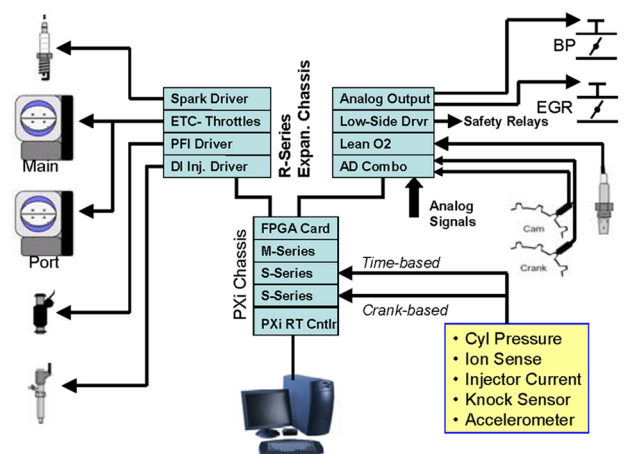


Figure 4. Schematic of test cell single-cylinder engine controller with real-time heat release analysis.

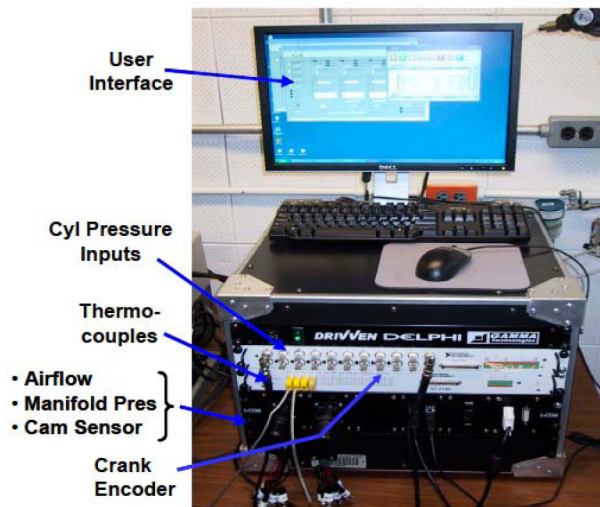


Figure 5. Residual Estimator Tool (RET).

METHODOLOGIES: TEST AND ANALYSIS

The injection process is very important to achieve the necessary fuel-air mixing and stratification control for GDCI combustion. Injection characteristics need to be developed systematically to minimize fuel consumption and emissions within system constraints such as combustion noise. Low injection pressure is desired to keep cost of injection system low and reduce fuel pump parasitics.

Fuel injection parameters are defined in Figure 6, where SOI1 to SOI5, Q1 to Q5 and PW1 to PW5 are the start-of-injection timings in crank angle degrees (CAD), injection quantities in cubic millimeters, and injector driver pulse-widths in milliseconds, respectively, for each of five injection events. Knowledge of the injection quantity is required for each injection event; however, both rail pressure and cylinder pressure are time-varying. Injection pressure pulsations induced by each pulse have a significant effect on fuel quantity delivered by subsequent pulses. This makes it impossible to simply determine injection quantities from average rail pressure, injection PW, and the injector calibration map.

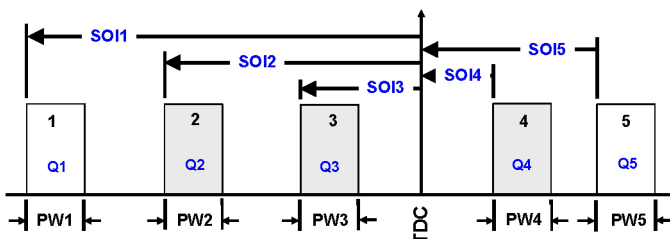


Figure 6. Injection parameter definitions.

Multiple-Injection Control Utility

A multiple-injection control utility that compensates for the effects of rail pressure pulsations was developed and implemented in the test cell engine controller using Labview [11]. It is shown schematically in Figure 7.

The user inputs are the SOI timings, the fractions of total fuel delivery, $Q\%$, and the desired engine IMEP. The measured inputs are IMEP from the cylinder pressure transducer, measured total fuel quantity from the fuel meter, crank-angle-resolved cylinder pressure and crank-angle-resolved injection pressure measured using a transducer located near the injector inlet. By processing the cylinder and injection pressure signals, with an embedded injector calibration, the required pulse-widths are determined. The algorithm also modulates commanded total Q for closed-loop PID control of IMEP to the desired test value while maintaining the desired fuel fractions for each injection. Similarly, closed-loop PID control of intake and exhaust pressure, injector rail pressure, EGR, and intake air temperature is used to improve speed and accuracy in setting engine test points.

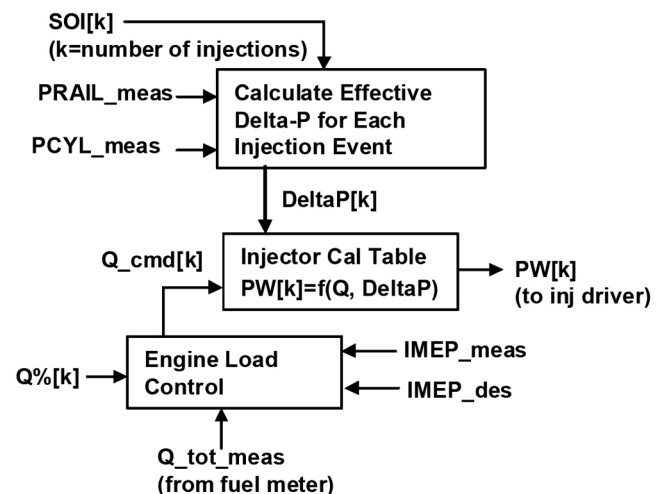


Figure 7. Multiple-injection pulse-width control with closed-loop IMEP control.

Design of Experiments, Response Surface Modeling and Optimization

The number of injection parameters is too large to permit use of traditional parametric test methods. Therefore state-of-the-art methods for design of experiments (DoE), response surface modeling (RSM) and optimization were applied. The model-based control (MBC) toolbox from Mathworks, Inc. [15] was used for this purpose.

Figure 8 shows a Stratified Latin Hypercube DoE design used to examine the effects of injection parameters with a triple-injection strategy. There are five “global” DoE variables. At