HISTORY OF GASOLINE DIRECT COMPRESSION IGNITION (GDCI) ENGINE- A REVIEW

MeisamAhmadiGhadikolaei

Department of Mechanical Engineering, A. M. U., Aligarh, U. P., India

Abstract

The first single-cylinder gasoline direct compression ignition (GDCI) engine was designed and built in 2010 by Delphi Companyfor testing performance, emissions and Brake specific fuel consumption (BSFC). Then after achieving the good results in performance, emissions and BSFCfrom single-cylinder engine, multi-cylinder GDCI engine was built in 2013. The compression ignition engine has limitations such as high noise, weight, PM and NO_X emissions compared to gasoline engine. But the high efficiency, torque and better fuel economy of compression ignition engine are the reasons of Delphi Company to use compression ignition strategy for building a new combustion system. The objective of the present review study involves the reasons of building of the GDCI engine in detail.

Keywords: *Delphi Company,Emissions, Multi-Cylinder GDCI engine andSingle-CylinderGDCI Engine.*

---***---

1. INTRODUCTION

1.1 Background of Gasoline Direct Compression Ignition (GDCI) Engine

Near-term regulations (Tier2 Bin 5/Bin 2 and Euro 6) for Corporate Average Fuel Economy(CAFE), CO2 emissions and regulated emissions including NO_X, CO, HC, and particulate matter (PM) are demanding advanced internal combustion (IC) engines with greatly improved combustion processes. While diesel engines are already very efficient, they are challenged in the US to meet future emissions standards at reasonable cost. Gasoline engines are preferred by customers in the US, but the efficiency of gasoline engines is relatively low. Homogeneous Charge Compression Ignition (HCCI) gasoline engines are dual-mode engines that utilize HCCI mode over a very limited low-load operating range. HCCI involves early injection and mixing of fuel such that subsequent compression of the mixture will cause auto ignition near or after top dead center. HCCI is very difficult to control in a practical vehicle application and is subject to misfires and high combustion noise. This requires advanced combustion feedback control including cylinder pressure sensing. While more efficient and lower emissions when in HCCI mode, the net efficiency on a drive cycle is only a few percent better than a stoichiometric SI engine with variable valve actuation. Current HCCI developments include GDI (gasoline direct injection), EGR, and turbocharging to extend load range; however, because HCCI engines require dual mode operation, they are limited by lower compression ratios associated with conventional gasoline engines. HCCI engines will likely see continued technical challenges. New technology is needed to greatly increase the efficiency of gasoline engines while maintaining low emissions and low cost. Therefore Gasoline Direct Injection Compression Ignition (GDCI) is a new combustion system that overcomes many of the fundamental limitations of other diesel and gasoline engines. GDCI provides the high efficiency of conventional diesel engines with unleaded regular gasoline. Compared to diesel fuel, gasoline has much higher volatility and longer ignition delay, which are key enablers to a partially premixed compression ignition combustion process. An important outcome is that gasoline can be injected late on the compression stroke at GDI-like fuel pressure (100 to 500 bar) to achieve a sufficiently premixed charge [1].

1.2 History of First GDCI Engine

In 2010, The US Department of Energy (DOE) selected Delphi, along with partners Hyundai America Technical Center (HATCI), Wisconsin Engine Research Consultants (WERC) and the University of Wisconsin-Madison (UW) for a $7.48-million grant to develop and to demonstrate a new high-efficiency vehicle concept. A key strategy for achieving the project goals is the further development of a new low-temperature combustion system, gasoline direct-injection compression-ignition (GDCI).

Mark Sellnau, Engineering Manager of Advanced Powertrain Technology at Delphi Powertrain, on the progress with GDCI at both the SAE 2012 High Efficiency IC Engines Symposium and the SAE 2012 World Congress in Detroit reported that GDCI, a low-temperature combustion (LTC) process for gasoline partially premixed compression ignition (PPCI), has been under consideration and development for about 5 years (Fig. 1), with efforts predating the 2010 DOE funding. Phase I of the project concentrates on fuel efficiency improvements using EMS, GDI, and advanced valve-train products in combination with technologies to reduce friction and parasitic losses. Phase II of the project will develop and demonstrate improved thermal efficiency from in-cylinder combustion with gasoline direct compression ignition. GDCI uses a high compression ratio with multiple late injection(MLI) - similar to diesel - along with intake boost and moderate EGR for high efficiency with low NO_X and PM over the entire speed-load map. The relatively long ignition delay and high volatility of pump gasoline combined with an advanced injection system and variable valve actuation provides controlled mixture stratification for low combustion noise [2].

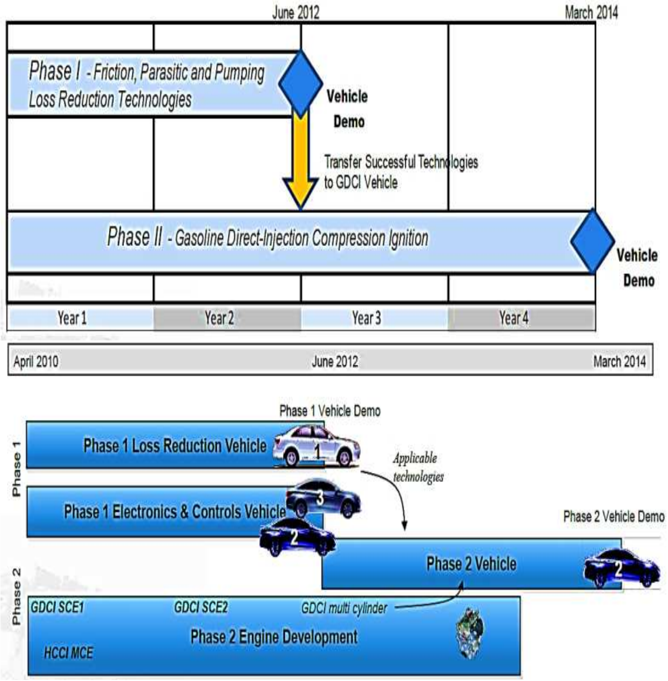

Fig -1: Delphi Scheduled Time Table for Producing Multi-Cylinder GDCI Engine in 2012[3]

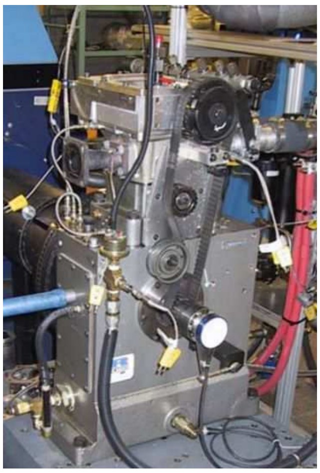

Fig -2: Single-Cylinder GDCI (Hydra) Test Engine [4]

Delphi team reported that among the objectives of the work reported in the paper [5] were 1) to determine the best injection strategies for low NO_X and PM using low-to-moderate injection pressures; and 2) to evaluate an engine concept for full-time operation over the speed-load map from idle to full load. Use of variable valve lift profiles was instrumental in enabling full-time GDCI operation. The team developed and tested five different injectors.

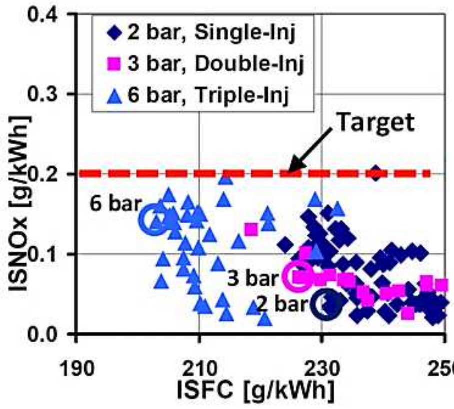

Fig -3: Single-Cylinder *E*ngine Test Results with one of the Five Injectors for 1500 rpm-2bar IMEP, 1500 rpm-3bar IMEP, and 1500 rpm-6bar IMEP [5]

Sellnau reported results derived from testing on a single-cylinder research engine as shown in Fig. 2. The cylinder head of the Ricardo Hydra light-duty single-cylinder engine has four-valves with double-overhead camshafts and central injection. The aluminum cylinder head is rated at 200 bar peak cylinder pressure (PCP). For all tests, intake air temperature was 50 C.

He also explained the experiments and results as follows:

- At a low-load condition of 1500 rpm-2 bar IMEP, Delphi used a secondary-exhaust-valve-lift event to rebreathe hot exhaust gas and promote auto-ignition. A “BDC” (Bottom Dead Center) intake cam was also used to maximize the effective compression ratio. Even though heat losses increased somewhat due to the rebreathing, they obtained good indicated specific fuel consumption (ISFC) of about 230 g/kWh, stable combustion, and exhaust port temperatures of about 250 C.
- At a medium-load condition of 1500 rpm-6 bar IMEP, injector developments combined with a MLI strategy (triple) and low swirl produced the best ISFC and lowest smoke. The most advanced injector design did not require swirl to achieve very low smoke and NO_X levels. Measurements of exhaust particulate size distribution showed that very low PM emissions could be obtained with this combustion system.

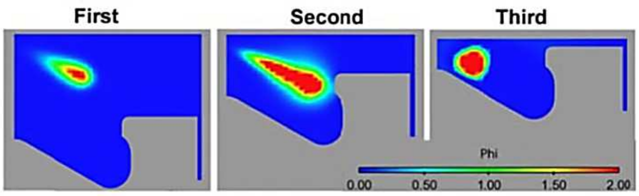

Fig -4: KIVA Simulation of Triple Injection Process.The Piston is seen rising in each frame [5]

- At higher loads, late intake valve closing was used to reduce cylinder pressure and temperature, and increase ignition delay. Delphi obtained a minimum ISFC of 181 g/kWh. Combustion noise, maximum pressure rise rate, and ringing intensity were in acceptable ranges, however, the correlation among these noise parameters was poor.
- For IMEP from 2 to 18 bar, engine-out NO_X and PM emissions were below targets of 0.2 g/kWh and 0.1 FSN, respectively, indicating that after-treatment for these species may be reduced or eliminated.
- Measurements of exhaust particulate size distribution indicated very low particle count, especially for a preferred injector with low levels of in-cylinder swirl.

Overall, single-cylinder engine tests of a GDCI combustion system indicate good potential for a high- efficiency, low-emissions powertrain. Additional testing and development on a multi-cylinder engine is needed, including cold-starting and transient operation.

Sellnau said that a modeled 1.8L GDCI engine for vehicle simulations showed large regions with fuel consumption of less than 190 g/kWh: loads of 6-20 bar, and speeds of 1800-3500 rpm. Applied in a mid-size passenger car, such an engine could potentially (without optimization or with a start-stop system, although with variation of gear ratios and shift schedules) deliver 60% improvement in city driving fuel economy, and 40% on US06, for a combined fuel economy improvement of about 51%. Finally in 2013, first phase is completed (Fig. 5) and Delphi made a multi-cylinder GDCI engine in as shown in Fig. 6.

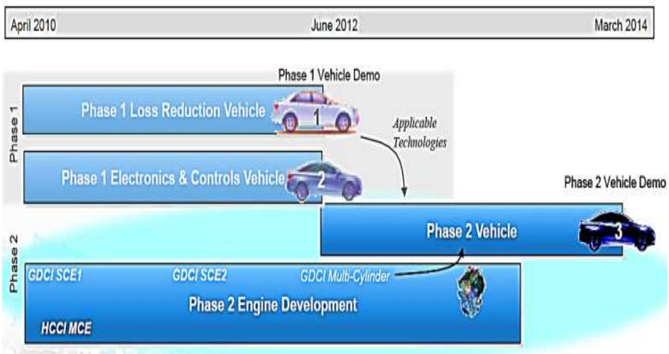

Fig -5: First Phase was completed by Delphi in 2013 [6]

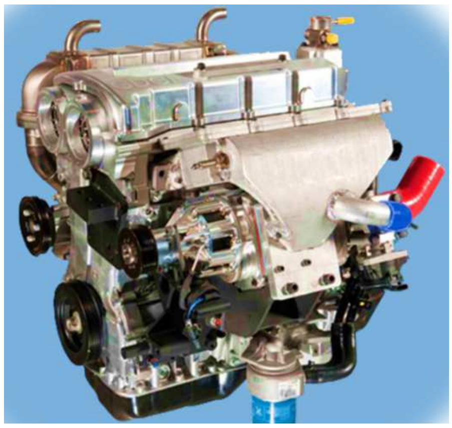

Fig -6: Multi-Cylinder GDCI Engine was made by Delphi in 2013 [6]

Specifications of multi-cylinder GDCI engine are as follows:

- 1.8L inline 4 cylinder
- 4 valves per cylinder
- 14.8:1 Geometric compression ratio
- Central-mounted DI Injector
- DOHC fully flexible valve-train
- Variable geometry turbocharger, supercharger and two intercoolers
- Cooled EGR
- 87 Octane E10 Gasoline

Preliminary, non-optimized Multi-cylinder Engine (MCE) and Single Cylinder Engine (SCE) results (2000 rpm-11bar) are shown in Fig. 7.

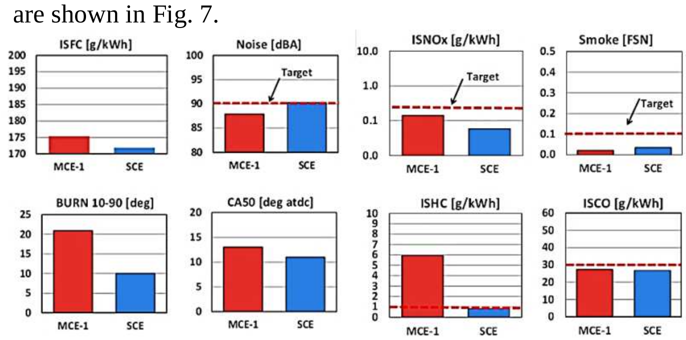

Fig -7: MCE Tests vs. SCE Results (2000 rpm-11bar) [6]

1.3 GDCI engine concept

The GDCI engine concept features high compression ratios (CR) and lean mixtures for ultra-high efficiency. Fuel is injected into a centrally-mounted piston bowl at high cylinder pressure and temperature late on the compression stroke. No fuel is injected during the intake stroke. The fuel and air rapidly mix and compression ignite in a controlled heat release process. As opposed to HCCI engines, the mixture is intentionally stratified. Because the fuel is injected late into a centrally-located piston bowl, no fuel enters the piston top-land and very high combustion efficiencies are possible.

Because of late injection, no end-gas exists, and classic combustion knock is not possible. Classic SI pre-ignition is also not possible. GDCI utilizes low temperature combustion (LTC) to reduce both NO_X and PM emissions simultaneously. Cooled exhaust gas recirculation (EGR) dilutes the mixture, increases the ignition delay period, and slows heat release rates for low combustion noise. Due to low charge temperatures, heat transfer during the cycle can be reduced for high cycle efficiency [1].

A schematic of the GDCI engine concept is shown in Fig. 8. The injector is central mounted with a symmetrical chamber and piston bowl. The engine is operated un-throttled and diluted with excess air or EGR, depending on load. The absence of classic knock and pre-ignition makes this concept a good choice for aggressive down-sizing, down-speeding, and boosting.

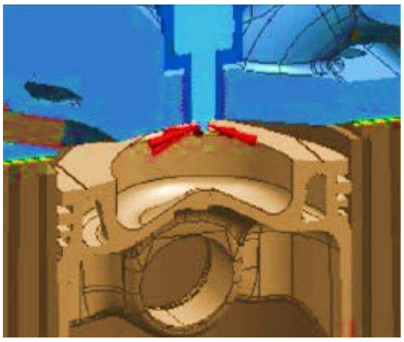

Fig -8: GDCI Engine Concept [4]

The GDCI injection strategy is central to the overall GDCI concept and is depicted in the Ø-T diagram shown in Fig. 9. The contours in Fig. 9 show simulated CO emissions concentration. The injection process involves one, two, or three injections during the compression stroke and are shown as Q1, Q2, and Q3 in Fig. 9. Each injection begins in the upper left of the Ø-T diagram (liquid) and vaporizes and mixes quickly to phi less than 2 by start of combustion. Wall wetting is minimized and fuel is kept away from cold zones such as the piston top-land and cylinder liner that may impede full oxidation. The fuel-air mixture must be stratified at the time combustion begins to achieve stable ignition and controlled heat release. To achieve low NO_X and low PM emissions simultaneously, combustion must occur “in the green box” shown in Fig. 9 (away from soot and NO_X formation regions). To also avoid CO emissions, which can compromise efficiency, combustion must occur in the region 0<Ø<1 with 1300<T<2200 degrees K. A primary attribute of this injection strategy is low fuel injection pressure.

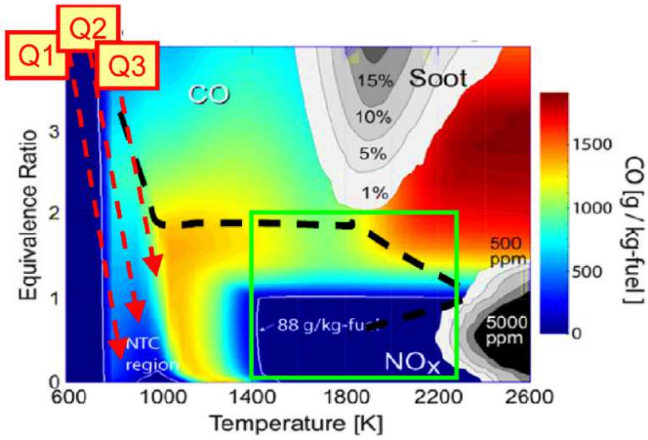

Fig -9: GDCI Injection Strategy Depicted on Ø-T Diagram with CO Concentration [4]

The efficiency mechanism for diesel, GDCI and SI engines are shown in Table 1.

Table 1: Efficiency Mechanism for Diesel, GDCI and SI Engines [6].

Efficiency Mechanism for Diesel & GDCI	Diesel	GDCI	Gasoline SI
Fuel Economy Benefit	25-30%	25-30%	Baseline
High Compression Ratio	~16:1	~15:1	~11:1
Unthrottled Operation (Pumping)	Yes	Yes	No
Lean Combustion (Gamma)	Yes	Yes	No
Negative Work in Pilot Injection	Yes	No	
Wall Losses with Swirl	High	Lower	

2. RESULTS REVIEW OF SINGLE AND MULTI-CYLINDER OF GDCI ENGINE PERFORMANCES

Before Delphi Corporation, many research works were performed by using gasoline fuel in compression engine. But those works were investigated in the format of direct injection compression ignition (DICI), homogeneous charge compression ignition (HCCI) and partially premixed compression ignition (PPCI) engines. The researchers who had done the works are listed as follows: Kalghatgiet. al. [7], [8], [9] and [10], Johansson (Lund University) et. al. [11], [12], [13] and [14], Weall [15], Reitzet. al. [16], [17], [18],

[19] and [20], Ciattiet. al. [21] and [22], and Yang [23]. In addition a groups at the University of Wisconsin [24] and [25] has also tested gasoline fuels in diesel engines.

2.1 Delphi Corporation et. al. [26]

In this work, a single-cylinder Hydra engine with Multiple-Injection strategy was used to study the potential of a high-efficiency combustion concept called gasoline direct injection compression-ignition (GDCI). It was reported that this combustion strategy benefits from the relatively long ignition delay and high volatility of regular unleaded gasoline fuel. It was also found that a triple-injection strategy with optimized injection timings and quantities produced the best fuel economy and duration of burn is shorter than both single-injection and double-injection. The triple-injection strategy enabled use of the lowest injection pressures compared to both single-injection and double-injection strategies.

Fig. 10 shows a comparison between GDCI and diesel at the 6 bar IMEP - 1500 rpm test condition reported in this study. Triple injection GDCI has about 9.5% better mass-specific fuel consumption and about 8% better indicated thermal efficiency than the diesel. However, because the diesel fuel has higher energy density than the gasoline used in these tests, GDCI has lower volumetric-specific fuel consumption than the diesel (4.5 %). Indicated specific mass CO2 emissions are shown in the bars on the right side in Fig. 10. GDCI has approximately 14 percent lower CO2 emissions on this basis.

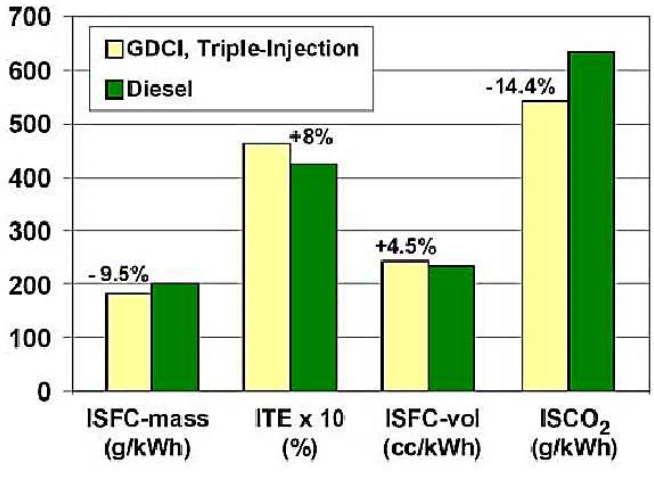

Fig -10: Fuel Consumption and CO2 Emissions Comparison; Triple-Injection GDCI vs. Diesel [26]

Using single-cylinder test results, brake specific fuel consumption (BSFC) for a multi-cylinder GDCI engine was estimated and then compared to data for various engine types as show in Fig. 11. The Volkswagen Jetta 2.01 turbo-diesel has BSFC of 250 g/kW-h [27]; a homogeneous gasoline direct-injected spark ignited engine [28] has BSFC of about 255; the Daimler 3.5L V6 spray-stratified engine [29] has BSFC of about 247; and a gasoline spark-ignited engine with increased cooled EGR [30] has BSFC of about 245 g/kW-h. The estimated BSFC for a multi-cylinder GDCI engine is about 210 g/kW-h or about 16 percent less than the Jetta diesel. This indicates that, at this important part-load operating condition, GDCI has good fuel economy potential.

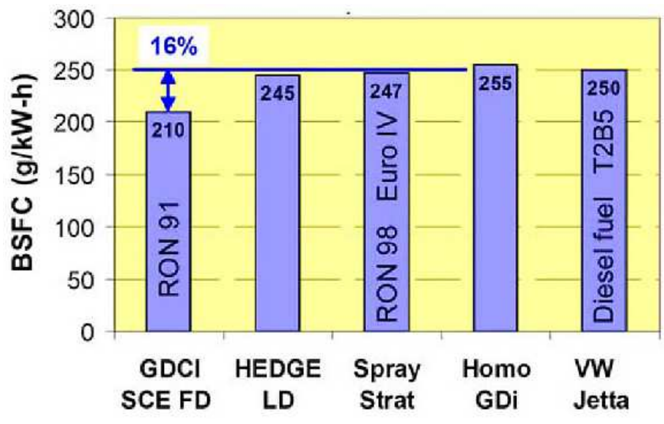

Fig -11: BSFC Comparison at 1500 rpm - 5 bar BMEP. GDCI BSFC Estimated from Single-Cylinder Engine Testing [26]

2.2 Delphi Corporation et. al. [5]

A single cylinder (GDCI) ignition combustion system was developed using RON 91 gasoline at low-to-moderate injection pressure. Fuel injection and valve-train technologies were key enablers. Low temperature combustion was demonstrated from 2 to 18 bar IMEP with diesel-like efficiency, NO_X less than 0.2 g/kWh, and PM emissions less than 0.1 FSN. Results suggest that after-treatment for NO_X and PM might be reduced or possibly eliminated, depending on legislated limits.

At low load condition of 1500 rpm-2 bar IMEP; a secondary-exhaust-valve-lift event was used to rebreathe hot exhaust gas and promote auto-ignition. A “BDC” intake cam was also used to maximize effective compression ratio. Even though heat losses increased somewhat due to rebreathing, good ISFC of about 230 g/kWh, stable combustion, and exhaust port temperatures of about 250 C were obtained.

At medium load condition of 1500 rpm-6 bar IMEP, injector developments combined with a multiple-late injection strategy (triple) and low swirl produced the best ISFC and lowest smoke. The most advanced injector design, injector E, did not require swirl to achieve very low smoke and NO_X levels. Measurements of exhaust particulate size distribution showed that very low PM emissions could be obtained with this combustion system.

At higher loads, late intake valve closing was used to reduce cylinder pressure and temperature, and increase ignition delay. Minimum ISFC of 181 g/kWh was obtained. Combustion noise, maximum pressure rise rate, and ringing intensity were in acceptable ranges, however, the correlation among these noise parameters was poor. Combustion noise measured by an AVL Combustion Noise Meter was chosen for optimization studies.

Overall, single-cylinder engine tests of a GDCI combustion system indicate good potential for a high efficiency, low-emissions powertrain. Additional testing and development on a multi-cylinder engine is needed, including cold-starting and transient operation.

2.3 Delphi Powertrain et. al. [4]

A multi-cylinder engine (MCE) GDCI engine was compared with single-cylinder engine. The MC engine is a 1.8L four-cylinder engine with 4-valves-per-cylinder and a central-mounted injector. A piston design based on single-cylinder tests was incorporated in the multi-cylinder engine. The boost system architecture is comprised of a variable geometry turbocharger, a supercharger, and two intercoolers. The EGR system is a compact, low-pressure system with an EGR cooler.

Preliminary tests were conducted at 2000rpm-11bar IMEP under conditions very similar to those used for single-cylinder engine (SCE) tests. Both the MCE and SCE were tested using Shell E10 gasoline. Tests for the MCE were simple parametric tests and are not considered optimized results. Individual-cylinder data was recorded, averaged, and presented as engine average data. Test results comparing the multi-cylinder engine to the single-cylinder engine are shown in Fig. 12. Overall, results are reasonably comparable for the two engines. ISFC was 175 and 172 g/kWh for the MCE and SCE, respectively. Combustion characteristics were somewhat different for the two engines with significantly longer 10-90 burn duration and somewhat later combustion phasing for the MCE. Combustion noise for the MCE was 88 dB and slightly lower than both the target and SCE results. Maximum pressure rise rate was also somewhat lower for the MCE.

NO_X and smoke emissions were well below targets for both engines (Fig. 13). While CO emissions were comparable, HC emissions for the MCE were high for this initial build. Such high levels are not believed to be typical and are being investigated for root cause. The higher HC for the MCE is reflected in lower combustion efficiency relative to SCE results.

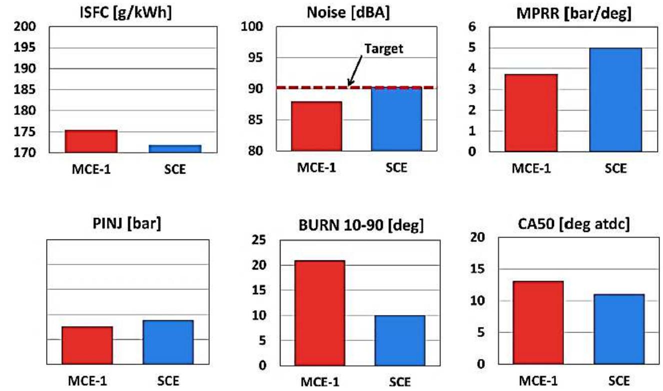

Fig -12: Preliminary Combustion Test Results for GDCI Multi-Cylinder Engine Compared to Single-Cylinder Engine at 2000 rpm-11bar IMEP [4]

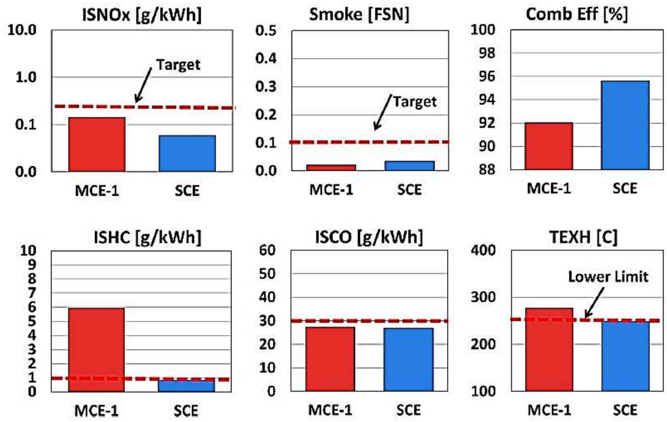

Fig -13: Preliminary emissions test results for GDCI multi-cylinder engine compared to single-cylinder engine at 2000 rpm-11bar IMEP [4]

It was also detailed heat release and efficiency loss analyses were performed to understand the fundamental processes involved in GDCI combustion. Heat losses and combustion losses were both very low, and contributed to indicated thermal efficiencies of approximately 47%. Losses associated with CO and HC emissions were higher than desired and are strong candidates for near term work.

CONCLUSIONS

The present review study has investigated that the GDCI engine was built in 2013 due to disadvantage of compression ignition (diesel) engine (high PM and NO_X emissions) and advantages of gasoline engines (low PM and NO_X emissions). The compression ignition engine has limitations such as high noise, weight, PM and NO_X emissions compared to gasoline engine. But the high efficiency, torque and better fuel economy of compression ignition engine are the reasons of Delphi Company to use compression ignition strategy for building a new combustion system. The GDCI is a new combustion system that overcomes many of the fundamental limitations of diesel and gasoline engines. The GDCI provides the high efficiency of conventional diesel engines with unleaded regular gasoline.

ACKNOWLEDGMENT

Author is thankful to Prof. Khalid Zaidi (Professor, Department of Mechanical Engineering, Aligarh Muslim University,Aligarh, Uttar Pradesh,India) for his counsel and guidance during progress of the review work.

NOMENCLATURES

BDC		Bottom Dead Center
CAFE		Corporate Average Fuel Economy
CE	percent	Combustion Efficiency
CNL	dBA	Combustion Noise Level
CO	g/kW-h	Carbon Monoxide Emissions
DoE		Design of Experiments
DOE		Department of Energy
EGR	percent by mass	Exhaust Gas Recirculation
FSN		Filtered Smoke Number
GDCI		Gasoline Direct Injection Compression Ignition
GDI		Gasoline Direct Injection
HATC		Hyundai America Technical Center
HC	g/kW-h	Hydrocarbon Emissions
HCCI		Homogeneous Charge Compression Ignition
HD		Heavy Duty
IMEP	bar	Indicated Mean Effective Pressure
ISCO	g/kW-h	Indicated Specific Carbon Monoxide Emissions
ISCO2	g/kW-h	Indicated Specific Carbon Dioxide Emissions
ISFC	g/kW-h	Indicated Specific Fuel Consumption
ISHC	g/kW-h	Indicated Specific Hydrocarbon Emissions
ISNOx	g/kW-h	Indicated Specific Nitrous Oxide Emissions
LD		Light Duty
LTC		Low Temperature Combustion
MCE		Multi-Cylinder Engine
MHRR	J/CAD	Max Heat Release Rate
MLI		Multiple Late Injection
NO_X		Oxides of Nitrogen Emissions
PCP	bar	Peak cylinder pressure
PHI (Ø)		Equivalence Ratio
P_{ing}		bar Injection Pressure
PM		Particulate Matter
PPCI		Partially Premixed Compression Ignition
P_{rail}	bar	Rail Pressure
PW	ms	Pulse Width
Q	mm3	Quantity Injected
Q%	percent	Quantity Injected as Percent of Total Fuel
RPM	rev/min	Revolutions per Minute
SCE		Single Cylinder Engine
SI		Spark Ignited
SOC	crank degrees	Start of Combustion
SOI	crank degrees	Start of Injection
TDC		Top Dead Center
UW		University of Wisconsin-Madison
WERC		Wisconsin Engine Research Consultants

REFERENCES

1. M. Sellnau, K. Hoyer, and J. Sinnamon, High-Efficiency InternalCombustion Engine and Method forOperating Employing Full-TimeLow-Temperature Partially-Premixed Compression ignition with Low Emissions, United States: Patent Application Publication, Pub. No.: US 2013/0213349 A1, Aug. 22. 2013.
2. http://www.greencarcongress.com/2012/04/gdci-20120425.html, 20.7.2013
3. K. Confer, J. Kirwan, and M. Sellnau, Gasoline Ultra Fuel Efficient Vehicle, Engine-Efficiency and Emissions Research Conference, ACE064, Merit Review DE-EE0003258, May 18, 2012.
4. M. Sellnau, J. Sinnamon, K. Hoyer, J. Kim, M. Cavotta, and H. Husted, Part-Load Operation of Gasoline Direct-Injection Compression Ignition (GDCI) Engine, SAE International, 04.08.2013.
5. M. Sellnau, J. Sinnamon, K. Hoyer, and H. Husted, Full-Time Gasoline Direct-Injection Compression Ignition (GDCI) for High Efficiency and Low NO_X and PM, SAE Int. J. Engines 5(2) doi: 10.4271/2012-01-0384, 2012.
6. K. Confer, J. Kirwan, and M. Sellnau, Gasoline Ultra Fuel Efficient Vehicle, Engine-Efficiency and Emissions Research Conference, ACE064, Merit Review DE-EE0003258, May, 17, 2013.
7. P. Risberg, G. Kalghatgi, H. Angstrom, and F. Wahlin, Auto-Ignition Quality of Diesel-Like Fuels in HCCI Engines, SAE Technical Paper, 2005-01-2127, 2005, doi:10.4271/2005-01-2127, 2005
8. G. Kalghatgi, P. Risberg, and H. Angström, Advantages of Fuels with High Resistance to Auto-Ignition in Late-Injection, Low-Temperature, Compression Ignition Combustion, SAE Technical Paper, 2006-01-3385, 2006, doi: 10.4271/2006-01-3385, 2006.
9. G. Kalghatgi, P. Risberg, and H. Angström, Partially Pre-Mixed Auto-Ignition of Gasoline to Attain Low Smoke and Low NOx at High Load in a Compression Ignition Engine and Comparison with a Diesel Fuel, SAE Technical Paper, doi: 10.4271/2007-01-0006, 2007.
10. G. Kalghatgi, Low NOx and Low Smoke Operation of a Diesel Engine using Gasoline-Like Fuels, ASME International Combustion Engine Division Spring Technical Conference, ICES2009-76034, 2009.
11. V. Manente, B. Johansson, and P. Tunestal, Partially Premixed Combustion at High Load using Gasoline and Ethanol, a Comparison with Diesel, SAE Technical Paper, doi: 10.4271/2009-01-0944, 2009.
12. V. Manente, B. Johansson, and P. Tunestal, Half Load Partially Premixed Combustion, PPC, with High Octane

Number Fuels, Gasoline and Ethanol Compared with Diesel, SIAT 2009 295, 2009.
13. V. Manente, B. Johansson, and P. Tunestal, Characterization of Partially Premixed Combustion with Ethanol: EGR Sweeps, Low and Maximum Loads, ASME International Combustion Engine Division 2009 Technical Conference, ICES2009-76165, 2009.
14. V. Manente, P. Tunestal, B. Johansson, and W. Cannella, Effects of Ethanol and Different Type of Gasoline Fuels on Partially Premixed Combustion from Low to High Load, SAE Technical Paper, 2010-01-0871, 2010, doi: 10.4271/2010-01-0871, 2010.
15. A. Weall, and N. Collings, Gasoline Fuelled Partially Premixed Compression Ignition in a Light Duty Multi Cylinder Engine: A Study of Low Load and Low Speed Operation, SAE Int. J. Engines 2(1):1574-1586, 2009, doi: 10.4271/2009-01-1791, 2009.
16. Y. Ra, J.E. Yun, and R. Reitz, Numerical Simulation of Diesel and Gasoline-fueled Compression Ignition Combustion with High-Pressure Late Direct Injection, Int. J. Vehicle Design, Vol. 50, Nos. 1,2,3,4. pp.3-34, 2009.
17. Y. Ra, J.E. Yun, and R. Reitz, Numerical Parametric Study of Diesel Engine Operation with Gasoline, Comb. Sci. and Tech., 181:350-378, 2009.
18. A. Dempsey, and R. Reitz, Computational Optimization of a Heavy-Duty Compression Ignition Engine Fueled with Conventional Gasoline, SAE Int. J. Engines, 4(1):338-359, 2011, doi: 10.4271/2011-01-0356, 2011.
19. Y. Ra, P. Loeper, R. Reitz, and M. Andrie, Study of High Speed Gasoline Direct Injection Compression Ignition (GDICI) Engine Operation in the LTC Regime, SAE Int. J.Engines, 4(1):1412-1430, 2011, doi: 10.4271/2011-01-1182, 2011.
20. Y. Ra, P. Loeper, M. Andrie, and R. Krieger, Gasoline DICI Engine Operation in the LTC Regime Using Triple-Pulse Injection, SAE Int. J. Engines 5(3):1109-1132, 2012, doi: 10.4271/2012-01-1131, 2012.
21. S. Ciatti, and S. Subramanian, An Experimental Investigation of Low Octane Gasoline in Diesel Engines, ASME International Combustion Engine Division Technical Conference, ICEF2010-35056, 2010.
22. D. Adhikary, Y. Ra, R. Reitz, and S.Ciatti, Numerical Optimization of a Light-Duty Compression Ignition Engine Fuelled with Low-Octane Gasoline, SAE Technical Paper 2012-01-1336, 2012, doi:10.4271/2012-01-1336, 2012.
23. H. Yang, S. Shuai, Z. Wang, and J. Wang, High Efficiency and Low Pollutants Combustion: Gasoline Multiple Premixed Compression Ignition (MPCI), SAE Technical Paper 2012-01-0382, 2012, doi:10.4271/2012-01-0382, 2012.
24. R. Hansen, D. Splitter, and R. Reitz, Operating a Heavy-Duty Direct-Injection Compression-Ignition Engine with Gasoline for Low Emissions, SAE Technical Paper 2009-01-1442, 2009, doi: 10.4271/2009-01-1442, 2009.
25. S. Kokjohn, R. Hanson, D. Splitter, and R. Reitz, Experiments and Modeling of Dual Fuel HCCI and PCCI Combustion Using In-Cylinder Fuel Blending, SAE Int. J. Engines 2(2):24-39, 2009, doi: 10.4271/2009-01-2647, 2009.
26. M. Sellnau, J. Sinnamon, K. Hoyer and H. Husted, Gasoline Direct Injection Compression Ignition (GDCI)-Diesel-like Efficiency with Low CO_2 Emissions, SAE International, 2011.
27. AVL FIRE Software, Version 2009, AVL Advanced, Simulation Technologies, Graz, Austria, 2009.
28. C. H. Yu, K. Park, S. Han, and W. Kim, Development of Theta II 2.4L GDI Engine for High Power and Low Emissions, SAE Technical Paper 2009-01-1486, 2009, doi:10.4271/2009-01-1486, 2009.
29. P. Luckert, “The New V6 Gasoline Engine with Direct Injection by Mercedes-Benz,” MTZ 11/2006 Vol 67, 2006.
30. T. Alger, J. Gingrich, C. Roberts, and B. Mangold, Cooled EGR for Fuel Economy and Emissions Improvement in Gasoline Engines, JSAE Paper 20105013, JSAE Annual Congress, 2010.

BIOGRAPHIES

MeisamAhmadiGhadikolaei, received the B.Sc. degree in Mechanical Engineering from Islamic Azad University, Sari branch, Iran in 2011, and received the M. Tech. degree in Mechanical Engineering (Thermal Sciences) under supervision of Prof. Khalid Zaidi, from Aligarh Muslim University, Aligarh, Uttar Pradesh, India in 2014.