

A Normally Aspirated Spark Initiated Combustion System Capable of High Load, High Efficiency and Near Zero NO_x Emissions in a Modern Vehicle Powertrain

2010-01-2196

Published
10/25/2010

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ABSTRACT

Turbulent Jet Ignition is an advanced spark initiated pre-chamber combustion system for an otherwise standard spark ignition engine found in current on-road vehicles. This next generation pre-chamber design simply replaces the spark plug in a conventional spark ignition engine.

Turbulent Jet Ignition enables very fast burn rates due to the ignition system producing multiple, widely distributed ignition sites, which consume the main charge rapidly. This high energy ignition system results from the partially combusted (reacting) pre-chamber products initiating main chamber combustion. The fast burn rates allow for increased levels of dilution (lean burn and/or EGR) when compared to conventional spark ignition combustion, with dilution levels being comparable to other low temperature combustion technologies (HCCI) without the complex control drawbacks.

Previous Turbulent Jet Ignition light load results at the world wide mapping point (1500 rev/min, 3.3 bar IMEP_n) have demonstrated an 18% improvement in fuel economy, with single digit ppm engine out NO_x emissions. This paper focuses on performance, efficiency, emissions and combustion effects of a Turbulent Jet Ignition system operated at unthrottled conditions with load variation achieved by altering the dilution level (excess air and/or EGR).

Turbulent Jet Ignition single cylinder experimental results at 1500 rev/min highlight a matched load operating range when compared to conventional spark ignition combustion, with identical peak BMEP and the ability to operate in an

unthrottled mode down to 3.9 bar IMEP_n with increasing dilution levels.

The high diluent fraction and resultant low temperature combustion has resulted in a peak indicated net thermal efficiency of 42% to be recorded together with near zero engine out NO_x emissions. This was achieved utilizing the engine's standard PFI fuel delivery system and a relatively low compression ratio of 10.4. Efficiency gains are attributed to a combination of combustion improvements, reduced heat losses and the near elimination of dissociation associated with low combustion temperatures. Peak efficiency improvements equate to an 11% relative improvement when compared to conventional stoichiometric spark ignition combustion. Results also indicate that jet ignition combustion has the potential to exceed 45% indicated net thermal efficiency (19% relative improvement) with a CR increase to ~14. The CR increase is made possible by the burn rate improvement associated with the distributed ignition system and the addition of side, wall guided DI. This would exceed the HCCI peak thermal efficiency of 43% in the same engine platform as there is no requirement to switch back to conventional spark ignition combustion at high load operation, which limits HCCI maximum CR for knock avoidance.

PRE-CHAMBER BACKGROUND

Combustion initiation in pre-chamber cavities in spark ignition engines began in the first part of the twentieth century with the Ricardo Dolphin engine [1, 2]. Since its inception, many variants of the pre-chamber combustion system have been developed, primarily to increase the engine's dilution tolerance and thermal efficiency. Currently,



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pre-chamber combustion systems exist in large bore stationary engines used for power generation, however they have failed to penetrate the vehicle market, with the notable exception of the Honda CVCC [3] of the 1970's. These divided chamber (pre-chamber) combustion systems are characterized by having either

- large or small pre-chamber volumes
- auxiliary pre-chamber fueling (charge stratification)
- large or small orifice(s) connecting the pre-chamber to the main chamber

The jet ignition system presented in this paper is characterized by features including: auxiliary pre-chamber fuelling, small orifices connecting the main and pre-chamber combustion cavities and a very small pre-chamber volume. The smaller orifice size causes the burning mixture to travel quickly through the orifice, which extinguishes the flame and seeds the main chamber with partially combusted pre-chamber products (radical species). It is then the reacting pre-chamber combustion products which entrain and ignite the main chamber charge through chemical, thermal and turbulence effects some distance away from the pre-chamber, thus producing a distributed ignition system. In addition, the smaller orifice creates a turbulent jet that penetrates deeper into the main charge. To avoid impinging on the combustion chamber wall, the pre-chamber volume has to be kept relatively small. Benefits of small pre-chamber volumes compared to their larger counterparts include negligible power loss and fewer hydrocarbon (HC) emissions due to the reduced crevice volume and combustion surface area. One of the earliest examples of this concept was researched by Gussak and colleagues under the term of LAG combustion [4,5,6]. A timeline of several jet ignition systems with small pre-chamber volumes is documented in [Table 1](#) [7, 8].

The review in [Table 1](#) highlighted that the concept of jet ignition was not new, with several well known researchers exploring this type of pre-chamber combustion system. However, the application and execution of previous systems have been laboratory based. The review highlighted that as of yet, state of the art hardware (injectors) and control systems (electronics) have not been applied to a modern pre-chamber design. Additionally, no research has been completed for this type of combustion system in a modern engine design using commercially available fuels for both the main chamber and pre-chamber combustion events. Hence, a next generation pre-chamber combustion system was designed and developed for this research, which will be termed Turbulent Jet Ignition. The modern pre-chamber design simply replaces the spark plug in a conventional spark ignition engine.

Table 1. Literature review of jet ignition research with small pre-chamber volumes (< 3% clearance volume) [7, 8].

Start Date	Jet Ignition System	Researchers	Reference
1950s	LAG - Avalanche Activated Combustion.	L.A. Gussak and colleagues	[4-6, 10, 12, 13]
Late 1970s	Flame Jet Ignition JPIC - Jet Plume Injection and Combustion PFJ - Pulsed Flame Jet PCJ - Pulsed Combustion Jet	A.K. Oppenheim and colleagues at the University of California, Berkeley and later by E. Murase at Kyushu University	[14-23]
1984	Swirl chamber spark plug	Reinhard Latsch at Bosch, Stuttgart	[24]
1992	HAIJ - Hydrogen Assisted Jet Ignition	H.C. Watson et al. at The University of Melbourne, Australia	[25-33]
1993	PJC - Pulsed Jet Combustion JDC - Jet Dispersed Combustion	Warsaw University of Technology	[34-36]
1993	HFJI - Hydrogen Flame Jet Ignition	Toyota College of Technology and Gifu University, Japan	[37, 38]
1999	APIR (Self ignition triggered by radical injection)	University of Orleans, France	[39, 40]
1999	Scavenged and unscavenged swirl chamber spark plugs	Pischinger et al. at Aachen University of Technology, FEV GmbH, Germany	[41]
1999	BPI - Bowl Pre-Chamber Ignition	Universitaet Karlsruhe and Multitorch GmbH in Germany	[42, 43]
2003	PJI - Pulse Jet Igniter	P. M. Najt et al. at General Motors	[44]
2005	HCJI - Homogeneous Combustion Jet Ignition	Robert Bosch GmbH	[45, 46]
2007	IAV pre-chamber spark plug with pilot injection	IAV GmbH and Multitorch GmbH, Germany	[47]
2009	TJI - Turbulent Jet Ignition	MAHLE Powertrain	[8, 48, 49]

With Turbulent Jet Ignition, the original PFI (homogenous) or DI (homogenous or stratified) fuel system supplying the main combustion chamber and majority of the fuel is carried over from the original OEM engine design. Besides the main chamber fuelling, under typical operating conditions, a small amount of additional fuel is injected into the pre-chamber just before ignition in the region of the spark plug. By locating the spark plug in a small pre-chamber (approximately 2% of the clearance volume), heat losses can be minimized and HC and CO emissions can be controlled. Employing a rich pre-chamber mixture leads to the production of radical species which have major benefits in chemically enhancing combustion [9,10,11]. Hence, it is beneficial to independently fuel the pre-chamber to enable high diluent fractions (lean burn and/or EGR) in the main combustion chamber.

A major advantage of the Turbulent Jet Ignition system is that it enables very fast burn rates due to the ignition system producing multiple, distributed ignition sites, which consume the main charge rapidly and with minimal combustion variability. The fast burn rates allow for increased levels of dilution when compared to conventional spark ignition combustion, with dilution levels being comparable to those achievable with homogeneous charge compression ignition (HCCI). In addition, Turbulent Jet Ignition has combustion control and hence speed/load range benefits when compared to HCCI, without the need for SI-HCCI combustion mode switching. The faster burn rates also allow for a base compression ratio increase when compared to conventional spark ignition combustion. This is achievable as the increased flame propagation (reduced flame front travel path) associated with a distributed ignition system reduces the likelihood of end-gas knock due to the reduced residence time [40, 50].

OBJECTIVES

The broad objective of this research is to extend the knowledge base of this form of combustion, providing a pathway forward for assessing pre-chamber and jet ignition technology in current day and potentially future vehicles. The specific objectives of this paper are to:

- Establish and compare the unthrottled operating load region that can be reached for both conventional spark ignition (homogeneous PFI) and Turbulent Jet Ignition combustion systems in normally aspirated form.
- Compare thermal efficiency and emission effects at unthrottled conditions for both combustion systems.
- Compare combustion burn parameters between spark ignition and Turbulent Jet Ignition combustion at unthrottled conditions with varying dilution.
- Determine unthrottled diluent limits (excess air and excess fuel limits) while still maintaining adequate combustion stability for both modes of combustion.

- Propose an in-vehicle load variation control strategy and subsequent emission clean up system for a Turbulent Jet Ignition combustion system.

MAHLE JET IGNITION SYSTEM

The MAHLE Turbulent Jet Ignition system [8, 48, 49] (Figure 1) builds on previous research completed in the field, with the objective of making the technology more feasible than other laboratory based jet ignition systems [7]. Hence, the system applies off the shelf hardware and modern control systems to a unique pre-chamber design. Additionally, the system has been developed to operate on readily available commercial fuels (gasoline, propane, natural gas), overcoming previous jet ignition hurdles of using hydrogen as the pre-chamber fuel. The system has been developed as a simple spark plug replacement in a modern spark ignition combustion system.

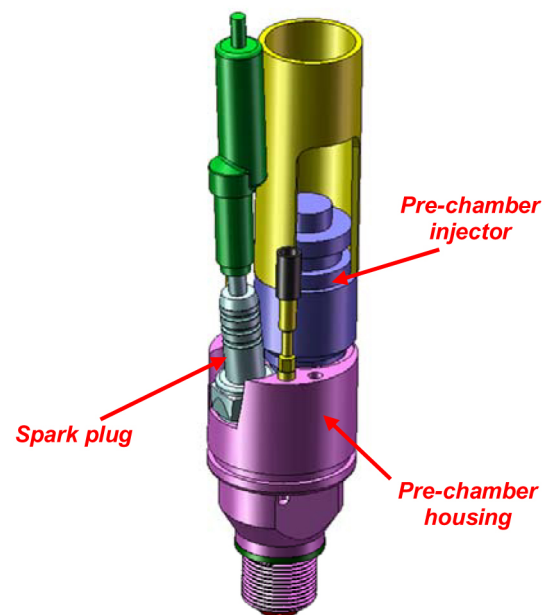


Figure 1. Computer generated image of the Turbulent Jet Igniter, designed to replace the spark plug in a modern spark ignition combustion system.

The list below highlights some of the novel and defining features of the MAHLE Turbulent Jet Ignition system.

- Very small pre-chamber volume
 - Minimize crevice volume, HC emissions, heat loss, surface-to-volume ratio effects and pre-chamber residual gas.
- Pre-chamber connected to main chamber by one or more small orifices
 - Promotes flame quenching and penetration into the main chamber. The reacting pre-chamber mixture initiates main

chamber combustion in multiple locations through chemical, thermal and turbulent effects

- Separately fuelled pre-chamber (flush mounted electronically controlled direct injector)
 - Allows a rich mixture to be contained in the pre-chamber while the main chamber is heavily diluted (excess air and/or EGR). Injector location assists in scavenging the pre-chamber residuals and minimizing crevice volume
- Separately fuelled main-chamber (electronically controlled PFI or DI)
 - Allows homogeneous or stratified main chamber mixtures (HC/NO_x emission control)
- Spark discharge initiated pre-chamber combustion (flush mounted electronically controlled spark plug)
 - Allows simple combustion phasing control.
- Research targets using readily available commercial fuels for both main and pre-chambers
 - Enables existing refueling infrastructure

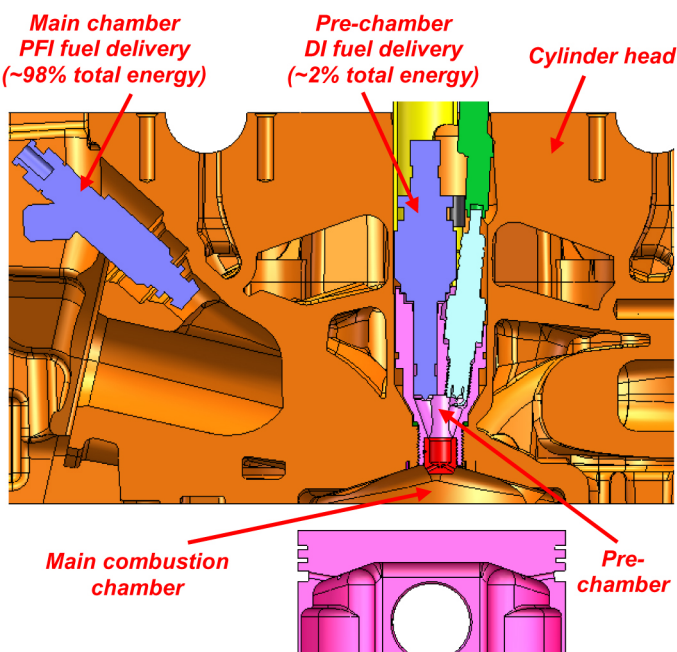


Figure 2. Computer generated image section view highlighting the Turbulent Jet Igniter centrally installed in the test engine's four valve, pent roof combustion system.

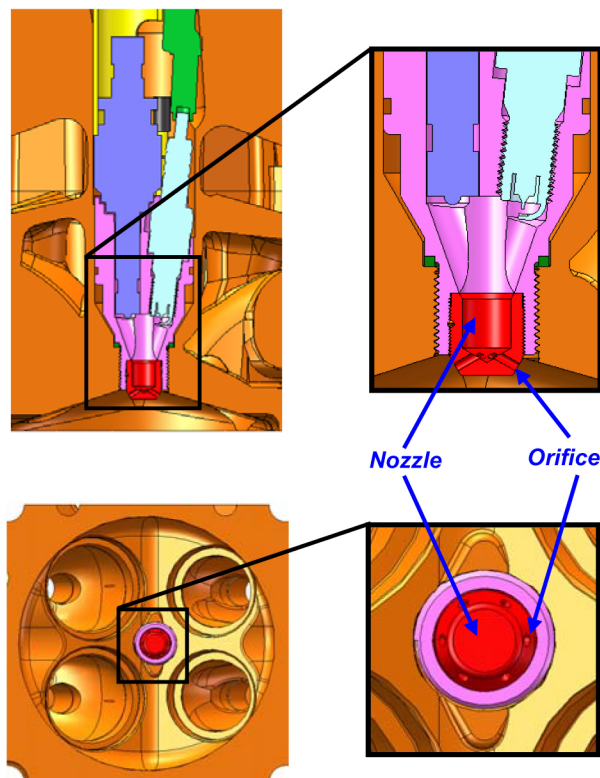


Figure 3. Computer generated image detail highlighting the Turbulent Jet Ignition pre-chamber and nozzle in the 4-valve pent roof combustion system.

Figure 2 highlights a section view of the modern design Turbulent Jet Ignition system installed in the test engine while Figure 3 displays some computer generated images highlighting the pre-chamber and nozzle assembly. In this particular jet ignition system, it is noted that the orifice diameter is kept small to promote flame quenching as the combustion products exit out of the pre-chamber into the main chamber. It is then the reacting pre-chamber mixture which initiates main chamber combustion in multiple locations through chemical, thermal and turbulent effects some distance away from the pre-chamber nozzle.

Table 2 lists the geometric specifications of the pre-chamber design used in experiments which were based from work completed by Watson and Dober [25, 51] in an optical access engine. Further improvements are expected with optimizing the pre-chamber nozzle and orifice geometry for this particular system. Nevertheless, the results presented highlight the capabilities of the jet ignition combustion system.

Table 2. Turbulent Jet Ignition pre-chamber specifications used in experiments.

PRE-CHAMBER VOLUME	1.3 cm ³ (2% clearance volume)
NUMBER OF ORIFICES	6
ORIFICE DIAMETER	1.25 mm
ORIFICE LENGTH	3 mm

Figure 4 highlights the Turbulent Jet Ignition sequence over one complete engine cycle. The key element which differs from a conventional spark ignition fueling strategy is the addition of pre-chamber fuel, which increases up to several percent addition of the total energy as the excess air dilution limit is increased. The pre-chamber fueling event is timed to end at approximately 50° before the spark discharge. This ensures that a rich plentiful mixture can be contained in the pre-chamber before spark discharge which has been proven to chemically enhance the combustion process through the formation of active radicals [9, 10, 30].

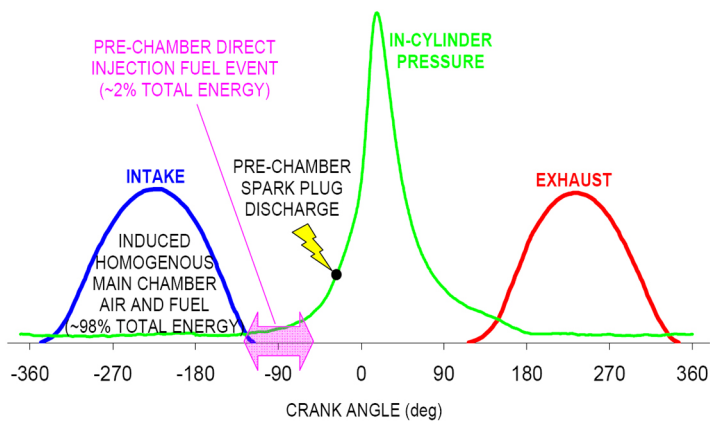


Figure 4. Timeline of Turbulent Jet Ignition sequence events over one complete engine cycle.

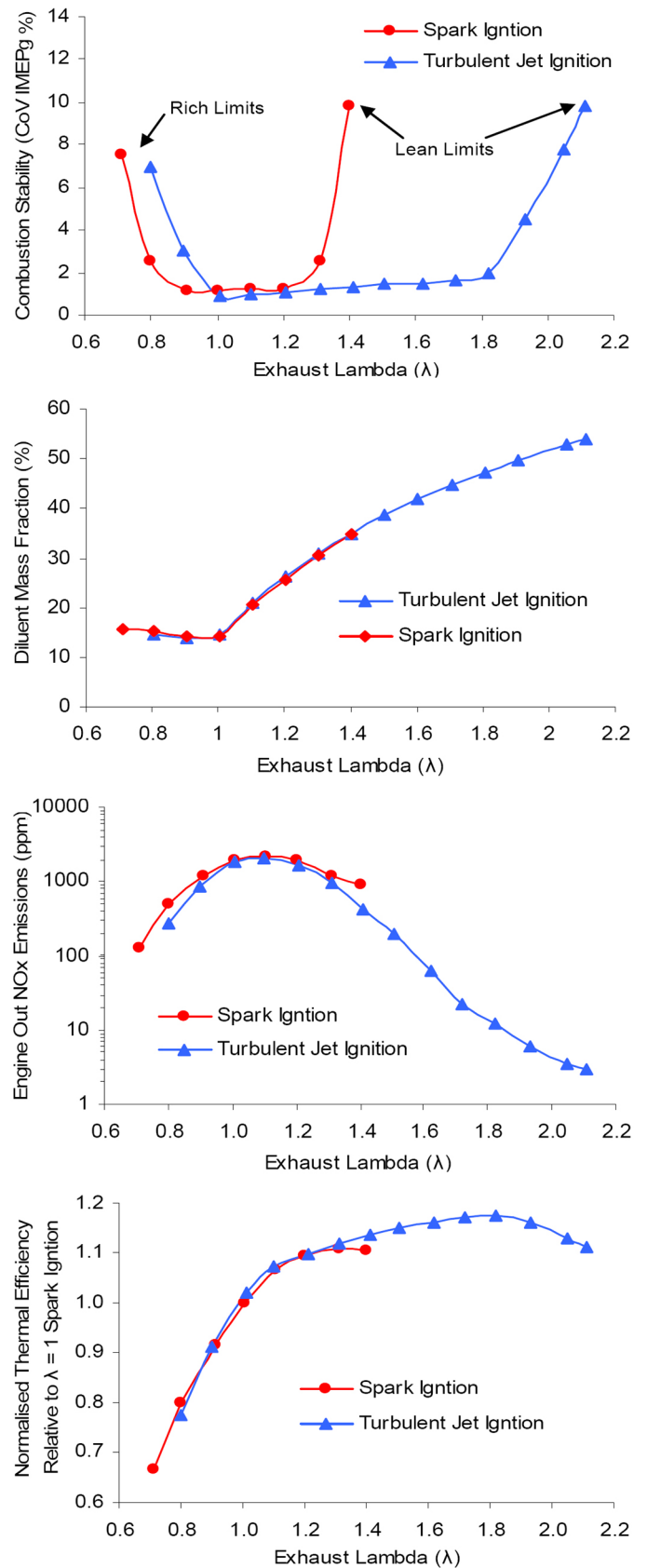


Figure 5. Comparison of spark ignition and Turbulent Jet Ignition combustion systems with increased dilution levels (excess air or excess fuel with 10 bar, 30°C NVO). 1500 rev/min, 3.3 bar IMEPn.

Figure 5 displays a sample of Turbulent Jet Ignition experimental results [8] taken from the test engine used in this study at a constant light load condition. Results at the world wide mapping condition of 1500 rev/min, 3.3 bar IMEPn are shown for the reader to gauge some background information on the unconventional combustion system at constant light load conditions before exploring unthrottled engine operation, with load variation achieved by altering the dilution level.

Figure 5 highlights the extension in the excess air dilution fraction of Turbulent Jet Ignition, which is capable of operating with adequate combustion stability near lambda 2. The extension in the operating limits is due to the improved combustion burn rates in the main chamber, facilitated by the distributed ignition system of the propagating jets exiting from the pre-chamber combustion event. Hence, the Turbulent Jet Ignition combustion system is capable of tolerating up to 54% mass fraction diluent (excess air and residual gas) while still maintaining adequate combustion stability at this speed/load operating point. This is a 50% diluent mass increase over that tolerated with spark ignition combustion. The high diluent fraction has enabled the pre-chamber combustion system to record an 18% improvement in fuel consumption when compared to conventional stoichiometric spark ignition. The efficiency improvements are due to a combination of combustion improvements, reduced heat losses, the near elimination of dissociation due to the low combustion temperatures and reduced engine throttling at part load. Additionally, the low temperature combustion has resulted in single digit ppm engine out NOx emissions with controllable levels of HC and CO emissions.

EXPERIMENTAL ENGINE

The single cylinder research engine used in experiments was derived from a current production level 14 Ecotec LE5 GM engine. The 0.6 liter research platform featured a flat top piston crown in a modern pent roof combustion system which incorporated double overhead camshafts and four valves per cylinder. The addition of continuously variable camshaft phasers for both the intake and exhaust enabled variable valve timing, with the available authority depicted in Figure 6.

Table 3 lists general test engine specifications. It is noted that intake and exhaust runner tracts were kept to standard lengths, which were both coupled to individual large plenum volumes in order to minimize the pressure fluctuations associated with the single firing event.

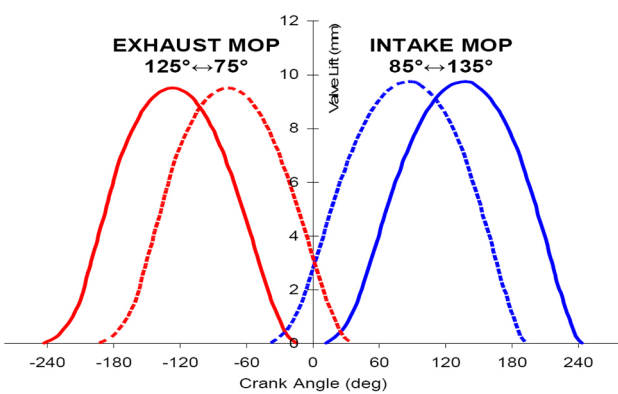


Figure 6. Range of intake and exhaust valve events with continuously variable camshafts.

Table 3. Test engine specifications.

TYPE	Normally aspirated single cylinder, 4 stroke, liquid-cooled, aluminum head/ block
DISPLACEMENT	0.6 liter
BORE x STROKE	88 x 98 mm
COMPRESSION RATIO	10.4
COMBUSTION CHAMBER	Pent roof, central ignition
VALVE ACTUATION	4-valve, DOHC, VVT
INTAKE	500 mm runner length, 19.1 liter plenum volume
EXHAUST	220 mm runner length, 19.1 liter plenum volume
FUEL DELIVERY	Spark Ignition: PFI Jet Ignition: main chamber PFI pre-chamber DI
FUEL	Spark Ignition: gasoline (EEE Indolene) Jet Ignition: main chamber (gasoline) pre-chamber (propane)
SPARK INITIATION	Inductive ignition system

The dilution strategy employed for experiments focused on finding both the lean and rich combustion stability limits while maintaining maximum hot internal residuals (hot EGR) using a negative valve overlap (NVO) strategy. Hence, the camshaft phasers were left in their parked positions for experiments, resulting in a 30° CA NVO (exhaust timing fully advanced while intake timing fully retarded) which also minimized the complexity of the experiments. Maintaining maximum hot residuals with NVO was beneficial as this minimized the heat lost to the intake and exhaust system, while minimizing pumping work when compared to other warm EGR re-breathing strategies [52]. Warm EGR has been proven to be beneficial in improving combustion stability (especially at low load) in highly diluted applications, enabling the diluent fraction to be further extended [53, 54] for further fuel economy and NOx emission reductions.