

A Single Fuel Pre-Chamber Jet Ignition Powertrain Achieving High Load, High Efficiency and Near Zero NOx Emissions

William P. Attard and Hugh Blaxill
MAHLE Powertrain

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ABSTRACT

Turbulent Jet Ignition is an advanced spark initiated pre-chamber combustion system for otherwise standard spark ignition engines found in current passenger 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 results from the partially combusted (reacting) pre-chamber products initiating combustion in the main chamber. The distributed ignition sites enable relatively small flame travel distances enabling short combustion durations and high burn rates. Multiple benefits include extending the knock limit and initiating combustion in very dilute mixtures (excess air and/or EGR), with dilution levels being comparable to other low temperature combustion technologies (HCCI), without the complex control drawbacks.

Previous Turbulent Jet Ignition experimental results have highlighted peak net indicated thermal efficiency values of 42% in a standard contemporary PFI engine platform. Additionally, the pre-chamber combustion system is capable of tolerating over 50% mass fraction diluent (combination of excess air and EGR) at part load, resulting in near zero engine out NOx emissions. This equates to a greater than 20% peak fuel economy improvement when compared to stoichiometric spark ignition in the same contemporary PFI engine platform. Although previous published results of this combustion system are very promising, the main hurdle of this system has been the dual fuel system, with liquid gasoline used in the main combustion chamber and small fractions of gaseous propane in the pre-chamber. The purpose of this paper is to demonstrate that this combustion system can operate on a single fuel, either gaseous propane or liquid gasoline, thus making the combustion system more practical for production applications.

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, 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 fuelling (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 [4-6]. Further review of pre-chamber initiated combustion systems has been documented [7], with additional information on previous jet ignition research also available in the literature [7-12].

A next generation pre-chamber jet ignition combustion system (Turbulent Jet Ignition) was designed and developed for this research. 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 can be carried over from the standard OEM engine design. Besides the main chamber fuelling, under typical operating conditions, a small amount of additional fuel is injected into the pre-chamber cavity to achieve a rich mixture just before ignition. Consequently, 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, widely distributed ignition sites, which consume the main charge rapidly. 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 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 (CR) 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 [13, 14].

OBJECTIVES

The specific objectives of this paper are to:

- Investigate the suitability of a sole gaseous fuel pre-chamber jet ignition combustion system using propane for both the pre-chamber and main chamber combustion events.
- Investigate the suitability of a sole liquid fuel pre-chamber jet ignition combustion system using gasoline for both the pre-chamber and main chamber combustion events.
- Determine maximum levels of diluent for the sole fuel jet ignition systems while still maintaining adequate combustion stability (5% CoV IMEPg).
- Compare fuel consumption and emission effects between the varying fuel jet ignition systems and conventional spark ignition combustion.
- Compare combustion burn parameters between the varying fuel jet ignition systems and conventional spark ignition combustion.

MAHLE JET IGNITION SYSTEM

The MAHLE Turbulent Jet Ignition system [8-12] (Figure 1, Figure 2) builds on previous research, with the objective of making the technology more production feasible than previous 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.

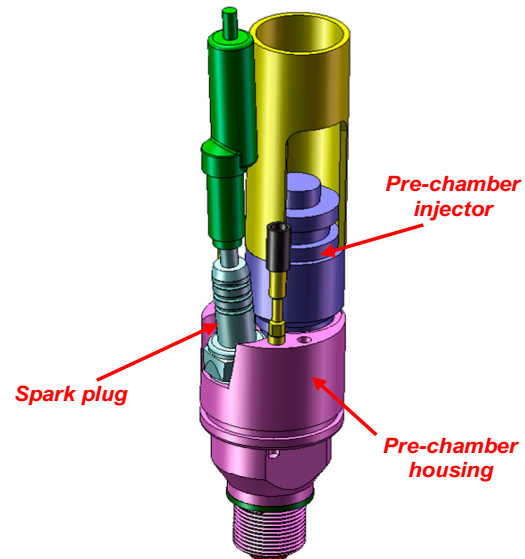


Figure 1: Design image of the Turbulent Jet Igniter, designed to replace the spark plug in a contemporary spark ignition combustion system.

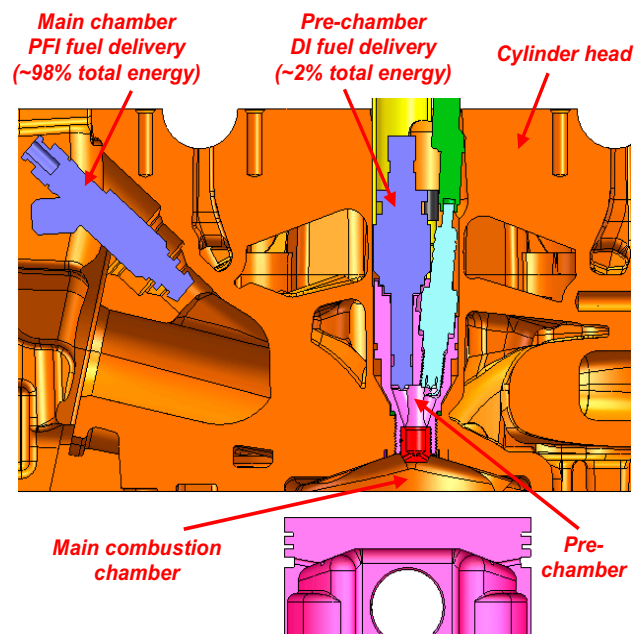


Figure 2: Section view highlighting the Turbulent Jet Igniter centrally installed in the test engine's four valve, pent roof combustion system.

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

- Very small pre-chamber volume
 - Minimizes 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 jet penetration into the main chamber. The reacting pre-chamber mixture initiates main chamber combustion in multiple locations through chemical, thermal and turbulence effects
- Separately fuelled pre-chamber (flush mounted electronically controlled direct fuel injector)
 - Allows a rich mixture to be contained in the pre-chamber while the main chamber is heavily diluted (excess air and/or EGR). Fuel 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)
 - Provides simple combustion phasing control

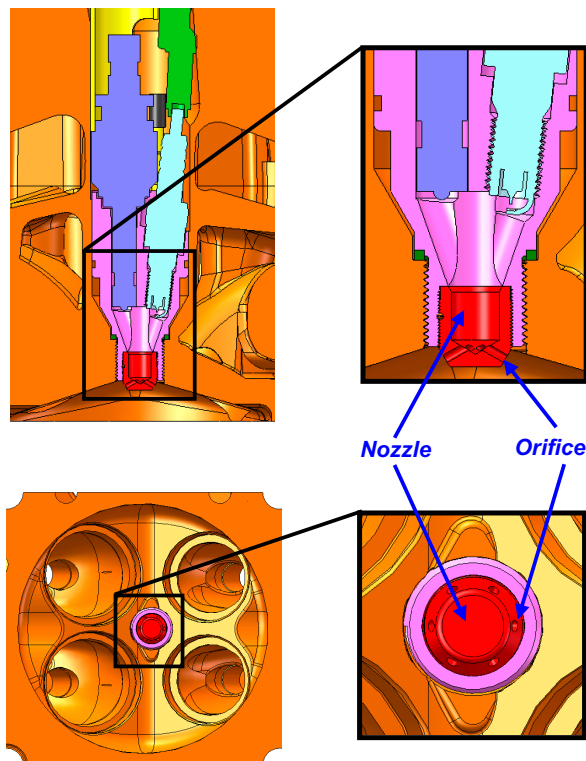


Figure 3: Design image highlighting the Turbulent Jet Ignition pre-chamber and nozzle in the 4-valve pent roof combustion system.

Centrally Located Jet Igniter (six jets)

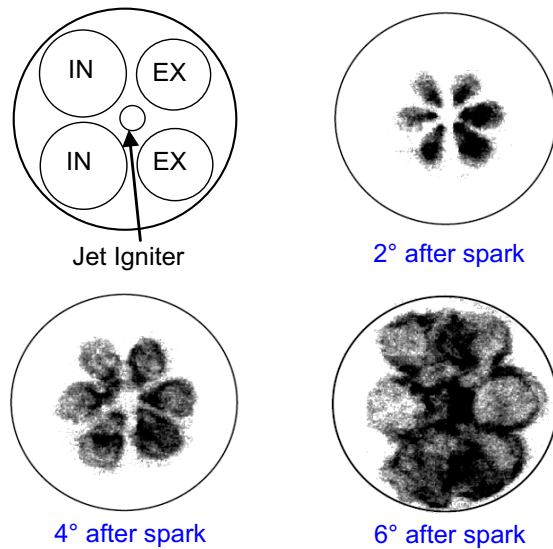


Figure 4: Jet ignition combustion [15, 16].

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 turbulence effects some distance away from the pre-chamber orifices. Figure 4 displays optical combustion images of jet ignition combustion taken from Watson's research group at the University of Melbourne [15, 16].

Figure 5 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 as the excess air dilution limit is increased [9]. The pre-chamber fuelling 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 shown to chemically enhance the combustion process through the formation of active radicals [17-21].

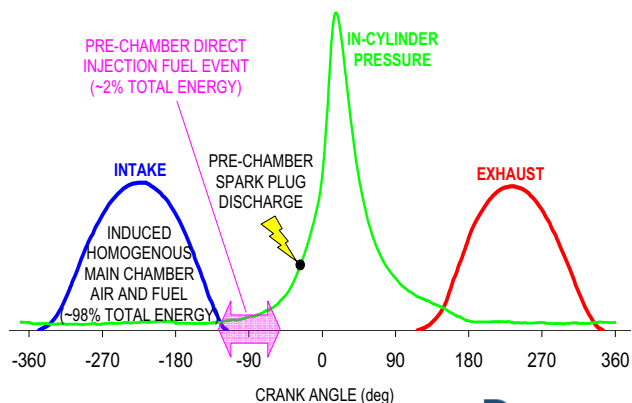


Figure 5: Jet Ignition sequence of events.

EXPERIMENTAL ENGINE

The single cylinder research engine used in experiments was derived from a current production level I4 PFI Ecotec LE5 (2.4 liter) GM engine. The 0.6 liter single cylinder 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. Standard production intake and exhaust camshaft profiles were retained. The intake and exhaust primary 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. Table 1 lists test engine specifications.

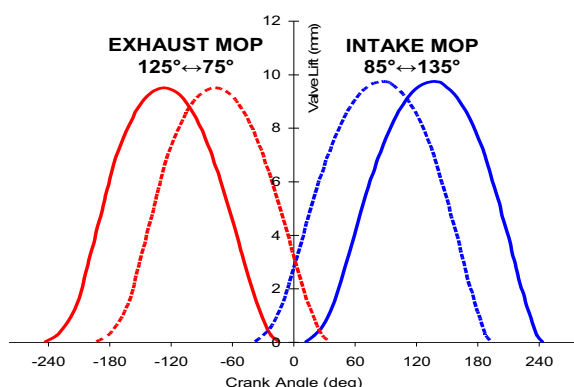


Figure 6: Range of intake and exhaust valve events with continuously variable camshaft phasers.

All lambda (λ) values presented in this paper are determined by analyzing the exhaust gas, with the exhaust lambda found by computation and confirmed directly with a wideband oxygen sensor. Hence for the jet ignition system, the exhaust lambda is inclusive of both the main and pre-chamber fuels, with the stoichiometric condition calculated for the combined main and pre-chamber fuel. Additionally, the thermal efficiency values presented for the jet ignition system are inclusive of the combined main and pre-chamber fuel consumption, which is heating value based.

To ensure data consistency, the dynamometer test rig regulated engine out coolant temperatures to $90^{\circ}\text{C} \pm 1.5^{\circ}\text{C}$ while oil sump temperatures were controlled to $85^{\circ}\text{C} \pm 1.5^{\circ}\text{C}$. The test rig measured liquid and/or gaseous fuel consumption on a mass basis directly. Engine out emissions were continuously sampled with a Horiba MEXA 200 series gas analyzer with heated exhaust sampling lines incorporated into the experimental setup. A flush mounted water-cooled Kistler 6041A pressure transducer was used to measure in-cylinder pressure in the main chamber, with TDC alignment achieved using a TDC probe. Additionally, in-cylinder pressure acquisition (0.5° CA sampling) and analysis was completed, enabling combustion parameters to be compared over a 200 engine cycle ensemble average.

Table 1: 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
SPARK INITIATION	Inductive ignition system, 40 mJ

BASELINE RESULTS

SPARK IGNITION versus JET IGNITION (dual fuel)

Extensive comparisons have previously been made by the authors between conventional spark ignition combustion and jet ignition combustion systems [8-12]. Combustion initiation for both baseline arrangements utilized a conventional automotive inductive ignition system, with 40 mJ of ignition energy. However, engine fuel and fuel delivery systems varied slightly between spark ignition and jet ignition systems (Figure 7) due to the addition of the pre-chamber fuel event. Spark ignition combustion experiments were completed with gasoline which was port fuel injected using a standard multi hole PFI injector at production fuel pressures (4 bar). However, jet ignition tests were completed with a mixture of gasoline for the main chamber and when required, very small quantities of propane for the pre-chamber when running excess air dilution. The gasoline which supplied the majority of the energy (96-100% depending on the operating condition) was port fuel injected into the main chamber using the same injector setup as the spark ignition tests. The propane was directly injected into the pre-chamber in gaseous form at low pressure (4 bar) using a production solenoid direct injector. Hence, the previously published data for the jet ignition system required a dual fuel arrangement, consisting of liquid gasoline for the main chamber and small amounts of gaseous propane for the pre-chamber.

The reasoning for not using a sole gasoline fuel system for initial jet ignition studies is the difficulty in accurately metering very small quantities of liquid fuel into the pre-chamber, when using commercially available direct injectors. Additionally, commercially available direct injectors are designed for fuel delivery in a much greater volume when compared to the very small pre-chamber cavity, resulting in combustion