

Flame Kernel Development for a Spark Initiated Pre-Chamber Combustion System Capable of High Load, High Efficiency and Near Zero NOx Emissions

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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 experimental results have highlighted peak net indicated thermal efficiency values of 42% in a standard modern engine platform. Additionally, the pre-chamber combustion system is capable of tolerating up to 54% mass fraction diluent (excess air and EGR) at the world wide mapping point of 1500 rev/min, 3.3 bar IMEP_n (~2.62 bar BMEP), resulting in an 18% improvement in fuel economy and near zero engine out NOx emissions.

This paper focuses on single cylinder experiments at the world wide mapping point, which attempted to extend the dilution level further by altering the flame kernel development inside the very small but rich pre-chamber environment. Turbulent Jet Ignition experiments incorporated previous techniques found to affect the dilution limits in

conventional spark ignition combustions systems. This included variations in spark plug type, orientation, location and electrode gap for the spark plug initiated pre-chamber combustion system. Experimental results highlighted that the pre-chamber combustion system is quite robust and largely unaffected by these changes, unlike conventional spark ignition combustion, as long as combustion inside the pre-chamber can be initiated. This occurs as combustion in the heavily diluted main chamber is driven by the chemical, thermal and turbulence effects of the propagating jet exiting the pre-chamber and not the flame front itself. Nevertheless, experiments found the eliminating the dead volume near the spark plug inside the pre-chamber, was beneficial in reducing the trapped residuals and thus enabled the dilution level to be slightly improved from an exhaust lambda of 2.08 to 2.14 (54 to 56% mass fraction diluent).

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. These divided chamber 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 [3,4,5]. A timeline of several jet ignition systems with small pre-chamber volumes is documented in [Table 1](#) [6, 7].

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.

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 [8,9,10]. 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 [11, 12].

Table 1. Literature review of jet ignition research with small pre-chamber volumes (< 3% clearance volume) [6, 7].

Start Date	Jet Ignition System	Researchers	Reference
1950s	LAG - Avalanche Activated Combustion.	L.A. Gussak and colleagues	[3-5, 9, 13, 14]
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	[15-24]
1984	Swirl chamber spark plug	Reinhard Latsch at Bosch, Stuttgart	[25]
1992	HAJI - Hydrogen Assisted Jet Ignition	H.C. Watson et al. at The University of Melbourne, Australia	[26-34]
1993	PJC - Pulsed Jet Combustion JDC - Jet Dispersed Combustion	Warsaw University of Technology	[35-37]
1993	HFJI - Hydrogen Flame Jet Ignition	Toyota College of Technology and Gifu University, Japan	[38, 39]
1999	APIR (Self ignition triggered by radical injection)	University of Orleans, France	[11, 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	[7, 48, 49]

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:

- Extend the dilution limits (excess air and EGR) of Turbulent Jet Ignition combustion by manipulating the flame kernel development inside the spark initiated pre-chamber.
- Gain insight into the effects of the flame kernel development process for this spark initiated pre-chamber combustion system.
- Apply and compare techniques previously found to alter the flame kernel development and hence dilution limit in conventional spark ignition combustion systems to Turbulent Jet Ignition.

MAHLE JET IGNITION SYSTEM

The MAHLE Turbulent Jet Ignition system [7, 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 [6]. 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.

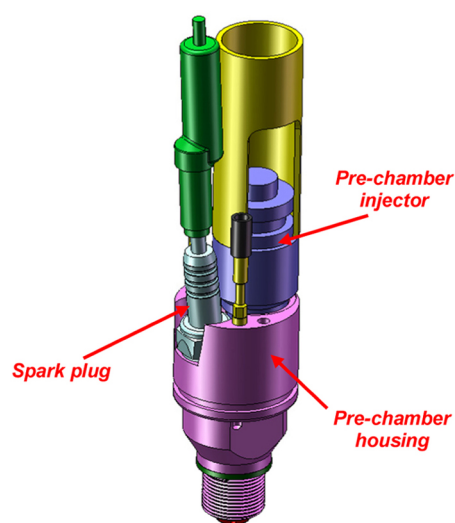


Figure 1. Computer generated image of the Turbulent Jet Igniter, designed to replace the spark plug in a modern spark ignition combustion system.

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

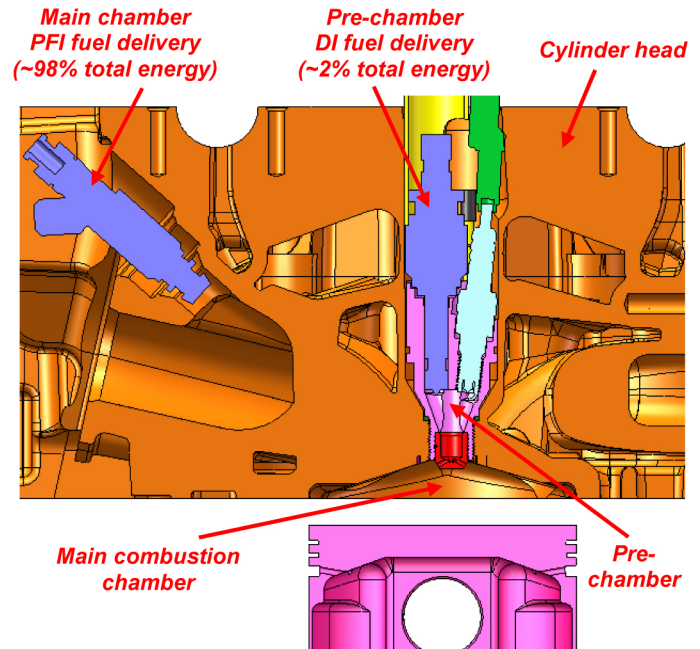


Figure 2. Computer generated image section view highlighting the Turbulent Jet Igniter centrally installed in the test engine's four valve, pent roof combustion system.

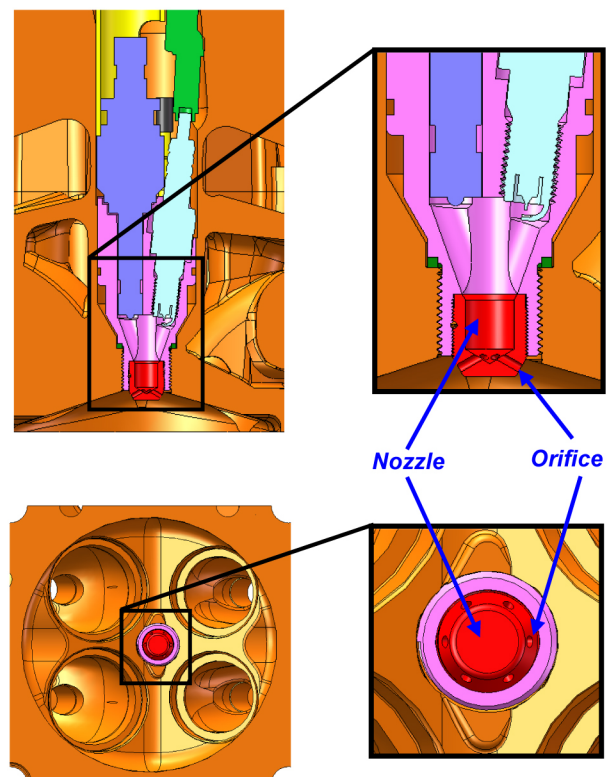


Figure 3. Computer generated image detail highlighting the Turbulent Jet Ignition pre-chamber and nozzle in the 4-valve pent roof combustion system.

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 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 [26, 50], who used hydrogen as the pre-chamber fuel in an optical access engine. Hence, this paper presents experimental results which have been obtained form a non-optimized pre-chamber nozzle and orifice geometry package, with further improvements expected. 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 [8, 9, 31].

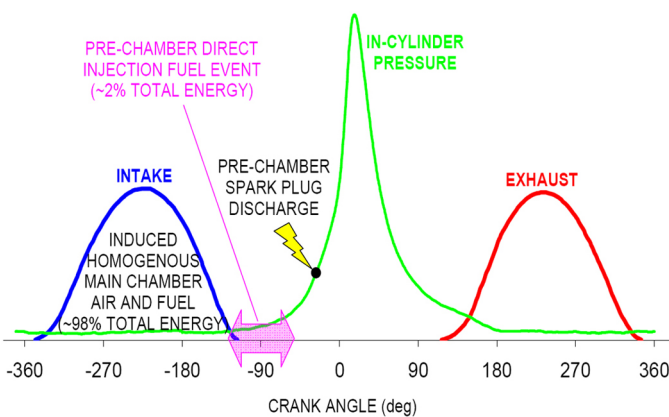


Figure 4. Timeline of Turbulent Jet Ignition sequence events over one complete engine cycle.

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 5. 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. Table 3 lists general test engine specifications.

Table 3. Test engine specifications.

TYPE	Normally aspirated single cylinder, 4 stroke, liquid-cooled, aluminum head/ block
DISPLACMENT	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

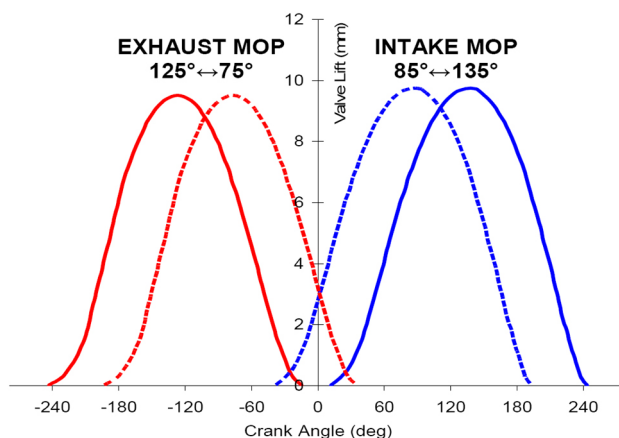


Figure 5. Range of intake and exhaust valve events with continuously variable camshafts.

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 [51]. 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 [52, 53] for further fuel economy and NO_x emission reductions.

To ensure data consistency, the dynamometer test rig regulated engine out coolant temperatures to 90°C ± 1.5°C while oil sump temperatures were controlled to 85°C ± 1.5°C. The test rig measured liquid fuel consumption directly using a Coriolis type mass flow meter which was confirmed with an inline positive displacement volumetric meter. In addition to the liquid fuel measurement, the pre-chamber gaseous fuel flow was measured directly with a thermal mass flow meter. To ensure data integrity, additional fuel flow checks were completed by calculating the fuel consumption from the measured air consumption (BSI042 sharp edged orifice plate) and air/fuel ratio at stoichiometric conditions. 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, with TDC alignment achieved using a Kistler TDC probe. TDC alignment was also confirmed by interpreting motored log pressure-volume data [54, 55]. Additionally, in-cylinder pressure acquisition (0.5° CA sampling) and analysis was completed using A&D's CAS

system, enabling combustion parameters to be compared over a 200 engine cycle average.

BASELINE EXPERIMENTAL RESULTS

SPARK IGNITION versus JET IGNITION

Before displaying the baseline results taken for spark ignition and Turbulent Jet Ignition systems [7], it is noted that the engine fuel and fuel delivery systems varied slightly between both combustion systems due to the addition of the pre-chamber fuel event. Spark ignition combustion experiments were completed with gasoline (EEE Indolene) which was port fuel injected at production fuel pressures (4 bar). However, jet ignition tests were completed with a mixture of gasoline (EEE Indolene) and when required, a very small amount of propane when running excess air dilution. The gasoline which supplied the majority of the energy was port fuel injected into the main chamber while the propane was directly injected into the pre-chamber in gaseous form at low pressure (4 bar), as shown pictorially in [Figure 2](#). Additionally for the jet ignition system, it is highlighted that the pre-chamber fuel flow rate was adjusted to achieve adequate combustion stability as the diluent fraction was increased ([Figure 6](#)). Hence, higher proportions of pre-chamber fuel were required to support combustion as the excess air diluent fraction was increased. For both spark ignition and jet ignition combustion systems, dilution levels (excess air or excess fuel) were increased until adequate combustion stability could no longer be maintained. For the purpose of this paper, adequate combustion stability is defined to be <10% CoV IMEP_g.

As the jet ignition system had varying lambda values in both combustion cavities as highlighted in the lower diagram of [Figure 6](#), all lambda values presented in this paper for both spark ignition and jet ignition combustion are determined by analyzing the exhaust gas, with the exhaust lambda found by computation (chemical balance of exhaust products) 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 pre-chamber main chamber fuel combination.