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A Turbulent Jet Ignition Pre-Chamber Combustion System for Large Fuel Economy Improvements in a Modern Vehicle Powertrain

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ABSTRACT

Turbulent Jet Ignition is an advanced pre-chamber initiated combustion system for an otherwise standard spark ignition engine found in current on-road vehicles. This next generation pre-chamber design overcomes previous packaging obstacles by simply replacing the spark plug in a modern four valve, pent roof spark ignition engine.

Turbulent Jet Ignition 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 (lean burn and/or EGR) when compared to conventional spark ignition combustion, with dilution levels being comparable to other low temperature combustion technologies (homogeneous charge compression ignition - HCCI) without the complex control drawbacks.

This paper focuses on preliminary performance, efficiency, emissions and combustion effects of a Turbulent Jet Ignition system operated with commercially available fuels at the world wide mapping point of 1500 rev/min, 3.3 bar IMEPn (~2.62 bar BMEP). Single cylinder experimental results highlight that the pre-chamber combustion system is capable of tolerating up to 54% mass fraction diluent while still maintaining adequate combustion stability. 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, the near elimination of dissociation due to the low combustion temperatures and reduced engine throttling. Additionally, the low temperature combustion has resulted in single digit ppm engine out NOx emissions with controllable levels of HC and CO emissions.

BACKGROUND / INTRODUCTION

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 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

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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 relative to their larger counterparts include negligible power loss and fewer 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].

For this research, the pre-chamber combustion system developed will be termed Turbulent Jet Ignition. 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 1-2% 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 [6,7,8]. 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 (lean burn and/or EGR) 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 phasing 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 (1-2 points) when compared to spark ignition combustion [9, 10].

A timeline of several jet ignition systems with small pre-chamber volumes is listed in Table 1. A comparison of the relevant differences between gasoline spark ignition, diesel, HCCI and jet ignition is also shown in Table 2.

OBJECTIVES

The review of past jet ignition systems (Table 1) has found that as of yet, state of the art hardware and control algorithms 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, the broad objective of this research is to extend the knowledge base of this relatively unknown form of combustion, providing a pathway forward for assessing jet ignition technology in current day and potentially future vehicles. The specific objectives of this paper are to:

- Compare fuel consumption and emission effects for conventional spark ignition and Turbulent Jet Ignition combustion systems.
- Compare combustion burn parameters between spark ignition and Turbulent Jet Ignition combustion.
- Determine maximum levels of diluent fraction while still maintaining adequate combustion stability (10% CoV IMEPg) for both modes of combustion.
- Gauge the Turbulent Jet Ignition combustion system control sensitivity to pre-chamber spark timing, pre-chamber injection timing and pre-chamber to main chamber fueling ratio.
- Investigate the sensitivity, robustness and reliability of this next generation Turbulent Jet Ignition system over the life of the experiments.

MAHLE TURBULENT JET IGNITION SYSTEM

Figure 1 displays a CAD image of the MAHLE Turbulent Jet Ignition system; designed to replace the spark plug in a current four valve, pent roof spark ignition combustion system.

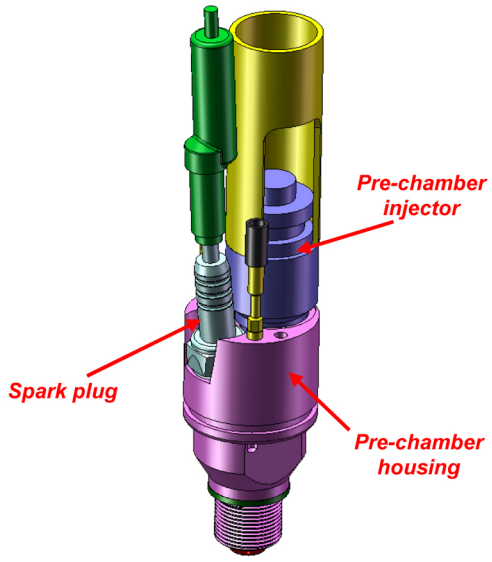


Figure 1. CAD image of the modern design Turbulent Jet Igniter, designed to replace the spark plug in a four valve, pent roof spark ignition combustion system.

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Table 1. Literature review of past jet ignition work with small pre-chamber volume (< 3% clearance volume).

Start Date	Jet Ignition System	Researchers Involved	Reference
1950s	LAG - Avalanche Activated Combustion.	L.A. Gussak and colleagues	[3-5, 7, 11, 12]
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	[13-22]
1984	Swirl chamber spark plug	Reinhard Latsch at Bosch, Stuttgart	[23]
1992	HAJI - Hydrogen Assisted Jet Ignition	H.C. Watson et al. at The University of Melbourne, Australia	[24-32]
1993	PJC-Pulsed Jet Combustion and JDC-Jet Dispersed Combustion	Warsaw University of Technology	[33-35]
1993	HFJI-Hydrogen Flame Jet Ignition	Toyota College of Technology and Gifu University, Japan	[36, 37]
1999	APIR (Self ignition triggered by radical injection)	University of Orleans, France	[9, 38]
1999	Scavenged and unscavenged swirl chamber spark plugs	Pischinger et al. at Aachen University of Technology and FEV Motorentechnick GmbH, Germany	[39]
1999	BPI- Bowl Pre-Chamber Ignition	Universitaet Karlsruche and Multitorch GmbH in Germany	[40, 41]
2003	Pulse Jet Igniter (PJI)	P. M. Najt et al. at General Motors	[42]
2005	(HCJI) Homogeneous Combustion Jet Ignition	Robert Bosch GmbH	[43, 44]
2007	IAV pre-chamber spark plug with pilot injection	IAV GmbH and Multitorch GmbH, Germany	[45]

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

  ◦ Allows flame quenching and penetration into the main chamber. Combusted pre-chamber products (chemical, thermal and turbulent effects) initiate main chamber combustion in multiple locations

• 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/NOx emission control)

• Spark plug initiated pre-chamber combustion (electronically controlled)

  ◦ Allows simple combustion phasing control, flush mounted spark plug.

• Research targets using readily available commercial fuels for both main and pre-chambers

  ◦ Enables the use of existing refueling infrastructure

Figure 2 highlights a section view of the modern design Turbulent Jet Ignition system installed in the test engine.

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Table 2. Generated comparison of common combustion technologies versus jet ignition [21, 46,47,48,49]. (PM: Particulate Matter, NOx: Oxides of Nitrogen, NSC: NOx Storage Catalyst, SCR: Selective Catalytic Reduction, SIDI: Spark Ignition Direct Ignition)

	Spark Ignition	Diesel	HCCI	Jet Ignition
Technology required for implementation	Spark plug, port or direct injector, 3-way catalyst	Direct injector, advanced emission clean up technology for PM and NOx	Variable valve lift and phasing, spark plug, direct injector, thermal management, advanced control system with closed loop combustion control, 3-way catalyst (stoichiometric) or a lean NOx trap, NSC or SCR may be required	Spark plug, direct injector (pre-chamber) and port or direct injector (main chamber), 3-way catalyst
Emissions	Very low emissions can be achieved with a 3-way catalyst	NOx and PM emission clean up technologies such as particle traps, lean NOx traps, NSC or SCR are expensive	Low engine out NOx but may not be low enough to not require expensive lean-NOx after-treatment to meet emission standards	Very low engine-out NOx emissions. A 3-way catalyst or oxidation catalyst is required
Peak efficiency	Least efficient	High efficiency	High efficiency relative to SI, near Diesel efficiency	High efficiency relative to SI, near Diesel efficiency
Speed / load range	Successful over production range	Successful over production range	Up to ~6 bar BMEP (normally aspirated). Can be extended with boost / cooled EGR concept 1000-4000 rev/min speed range	Successful over production load range, limited data available at high engine speeds
Fuel economy over drive cycle	Lowest drive-cycle fuel economy	Best drive-cycle fuel economy. Up to 30% improvement over SI	Up to 10-15% improvement relative to spark ignition	Up to 20% improvement relative to spark ignition
Controls	Least complicated control strategy	Complicated control strategy to ensure emission clean-up	Most complicated control strategy that must manage mode transitions and transients	Control strategy similar to SIDI with multiple pulse injections
NVH (noise)	Least noise	Combustion generated noise requires engine compartment silencing	Noise similar to diesel, requiring engine compartment silencing	In the range of spark ignition
Engine structure	Lightest and least expensive	Must design for very high rates of combustion pressure rise adding cost and weight	High rates of pressure rise add cost and weight due to structural concerns	Similar to spark ignition
Reliability	Very reliable	Very reliable	In R&D phase	Unknown
Cost	Least expensive	Very expensive due to emission after-treatment	Very expensive	More expensive than SI but projected to be less expensive than Diesel or HCCI

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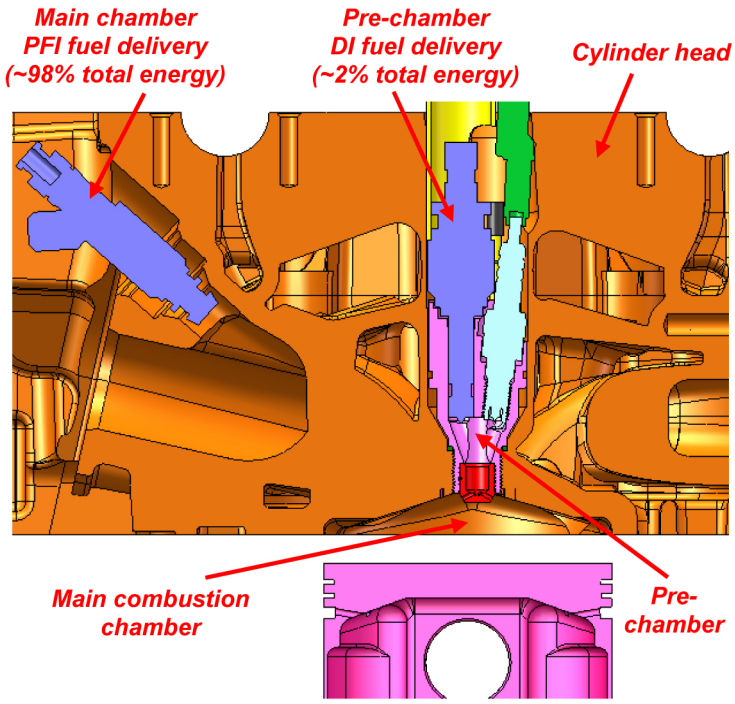


Figure 2. CAD image sectional view highlighting the Turbulent Jet Igniter centrally installed in the test engine's four valve, pent roof combustion system.

Figure 3 displays some CAD images highlighting the pre-chamber and nozzle assembly. The system was designed with a replacement nozzle which allows for geometric development (orifice variations) without the need to manufacture a complete new assembly. This paper presents initial jet ignition experimental results which have been obtained from a non-optimized nozzle and orifice geometry package.

In this particular jet ignition system, it is noted that that the orifice diameter is kept small to enable the pre-chamber flame front to be extinguished (flame quenching) as the combustion products exit out of the pre-chamber into the main chamber. Hence it is the chemical, thermal and turbulence effects of the partially combusted pre-chamber products that initiate the main chamber combustion in multiple locations and not the flame front itself exiting the pre-chamber.

Table 3 lists the geometric specifications used in experiments which were based from work completed by Watson and Dober [24, 50], who used hydrogen as the pre-chamber fuel in an optical access engine.

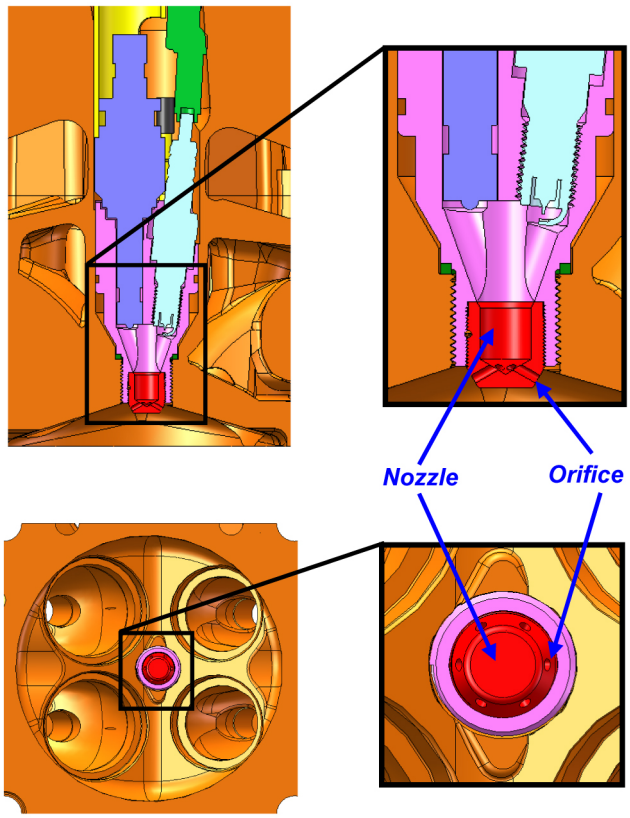


Figure 3. CAD image detail highlighting the Turbulent Jet Ignition pre-chamber and nozzle in the 4-valve pent roof combustion system.

Table 3. Turbulent Jet Ignition pre-chamber specifications.

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 (~2% of total energy). 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 which has been proven to chemically enhance the combustion process through the formation of active radicals [6, 7, 29].

EXPERIMENTAL ENGINE

The single cylinder research engine used in experiments was derived from a current level I4 production engine. The 0.6 liter research platform featured a flat top piston crown in a modern pent roof combustion system which incorporated

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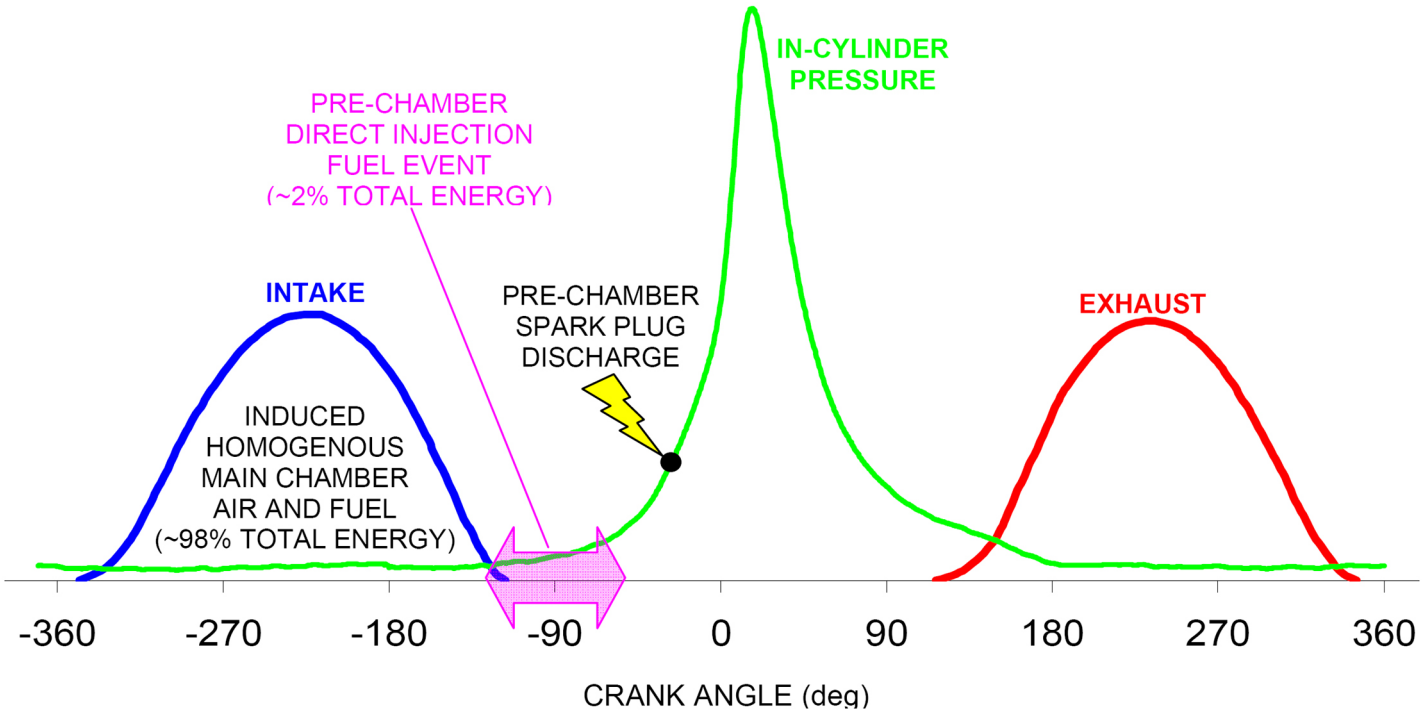


Figure 4. Timeline of Turbulent Jet Ignition sequence events over one complete engine cycle.

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 4 lists general test engine specifications.

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). 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 NOx emission reductions.

Table 4. 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
VALVE ANGLE	18° from vertical (inlet) 16° from vertical (exhaust)
VALVE SIZE	35.1 mm (inlet) 30.1 mm (exhaust)
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)

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