

Ignition Energy Development for a Spark Initiated Combustion System Capable of High Load, High Efficiency and Near Zero NOx Emissions

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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 type of 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 at the world wide mapping point of 1500 rev/min, 3.3 bar IMEPn (~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, which reduced the ignition energy of the spark initiated pre-chamber combustion system from 75 to less than 5 mJ. Experimental results highlight that the pre-chamber combustion system is quite robust and largely unaffected by ignition energy changes, unlike conventional spark ignition combustion which typically requires high amounts of energy (over 50 mJ) under diluted (lean burn/EGR) operation. This occurs as jet ignition combustion in the heavily diluted main chamber is driven by the chemical, thermal and turbulent effects of the

propagating jet exiting the pre-chamber and not the flame kernel growth and subsequent travelling flame front as in spark ignition combustion. Consequently, results show the potential to significantly reduce the ignition energy demand and hence ignition coil and spark plug size for the Turbulent Jet Ignition combustion system. This has additional benefits in improving component longevity, reducing ignition system costs and aiding in cylinder head packaging.

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 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 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 next generation pre-chamber design presented in this research simply replaces the spark plug in a conventional pent roof, modern four valve spark ignition engine. Additionally, 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 [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 (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 [11, 12].

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

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	HAI - 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 Motorentechnik 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	MAHLER Powertrain	[48]

OBJECTIVES

The broad objective of this research is to extend the knowledge base of this 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:

- Determine the ignition energy requirements for the spark discharge initiated pre-chamber combustion system.
- In the same test engine, compare the ignition energy requirements between conventional spark ignition and Turbulent Jet Ignition combustion systems.
- Compare combustion burn parameters for varying ignition energies for both modes of combustion.
- Determine the effects of varying ignition energy over varying fueling conditions, including excess air, excess fuel and stoichiometric operation.
- Determine the effects of varying ignition energy for load variations.

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

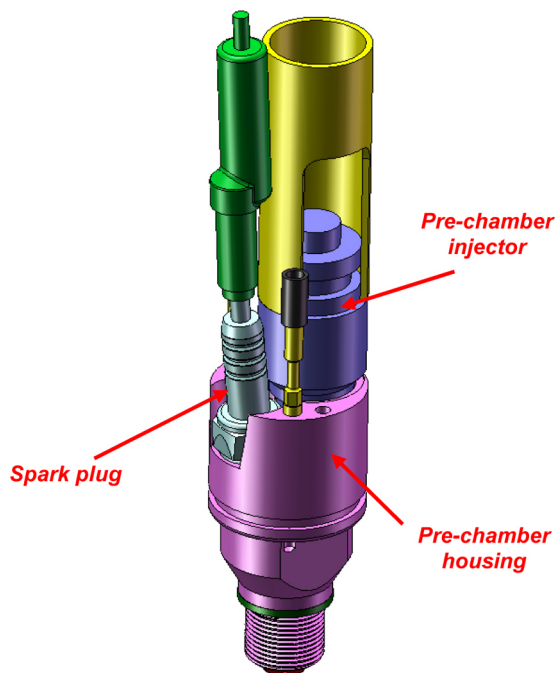


Figure 1. CAD image of the modern design Turbulent Jet Igniter, designed to replace the spark plug in a four valve, pent roof spark ignition combustion system.

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/NOx 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 the use of existing refueling infrastructure

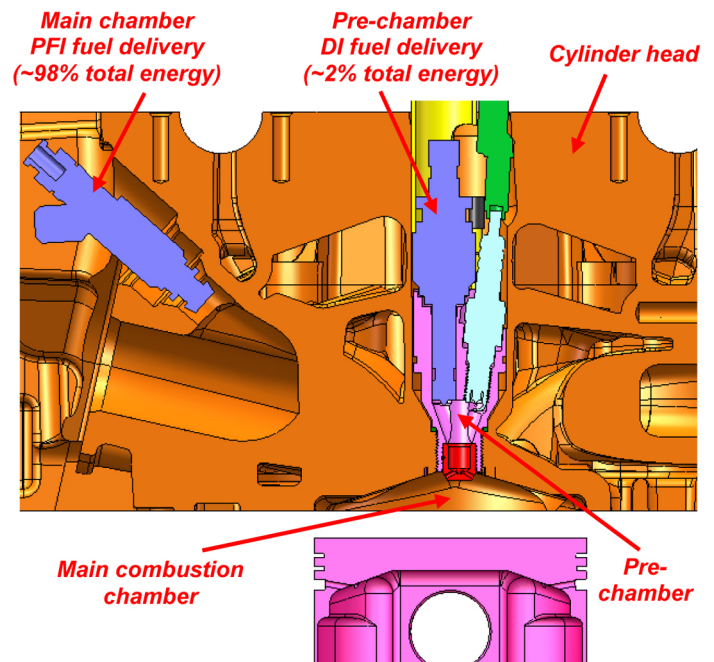


Figure 2. CAD image sectional view highlighting the Turbulent Jet Igniter centrally installed in the test engine's four valve, pent roof combustion system.

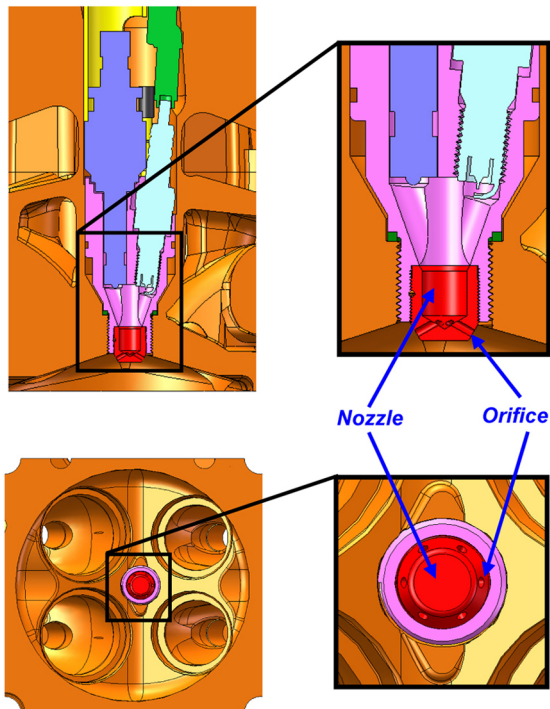


Figure 3. CAD image detail highlighting the Turbulent Jet Ignition pre-chamber and nozzle in the 4-valve pent roof combustion system.

Figure 3 displays some CAD 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 3 lists the geometric specifications of the pre-chamber design used in experiments which were based from work completed by Watson and Dober [26, 49], who used hydrogen as the pre-chamber fuel in an optical access engine. Hence this paper presents experimental results which have been obtained from 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 3. 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 displays optical combustion images of jet ignition combustion also taken from Watson's research group at the University of Melbourne [49, 50]. Although the images were taken with differing fuels when compared to the jet ignition system presented in this paper, they provide some flame visualization of the combustion system. The upper images in Figure 4 depict jet ignition combustion in a side ignited two valve engine design. In these images, the flame quenching effect out of the nozzle can clearly be identified, with the main chamber combustion initiating in the center of the combustion chamber noting the side installation of the pre-chamber jet igniter in this experimental setup. It is more difficult to visualize this flame quenching effect out of the pre-chamber nozzle (lower images of Figure 4) in the four valve centrally located jet igniter position due to the position of the camera relative to the jets exiting the pre-chamber.

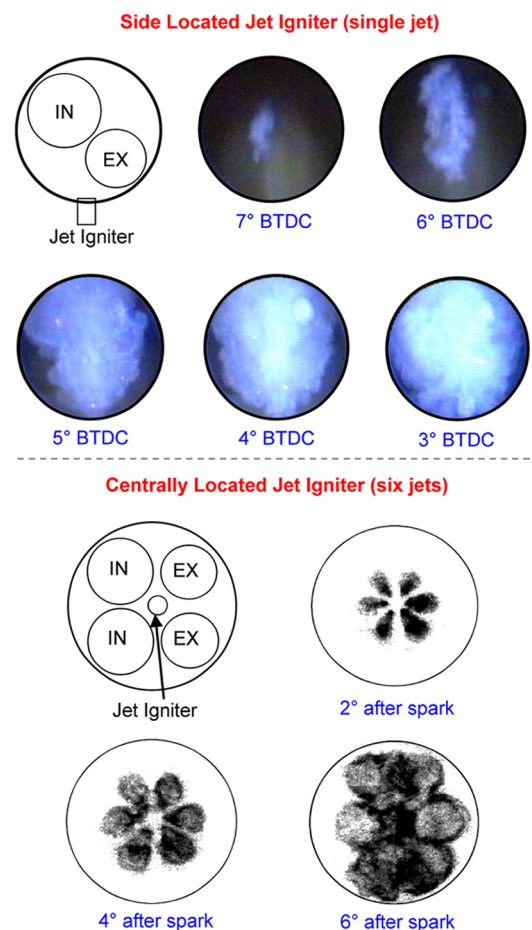


Figure 4. Optical images of jet ignition combustion using hydrogen pre-chamber fuel [49, 50]. The flame quenching effect as the combustion products exit out of the pre-chamber into the main chamber can be visualized, with the reacting pre-chamber mixture initiating main chamber combustion in multiple locations some distance away from the pre-chamber nozzle.

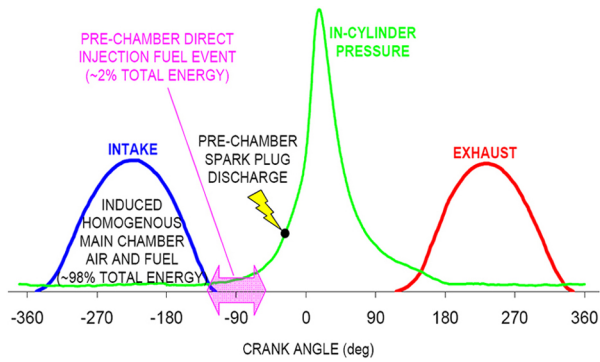


Figure 5. Timeline of Turbulent Jet Ignition sequence events over one complete engine cycle.

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 small quantities of pre-chamber fuel. The amount of fuel added to the pre-chamber increases as the excess air dilution limit is increased, which is discussed later in this paper. 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 the spark discharge which has been proven to chemically enhance the combustion process through the formation of active radicals [8, 9, 31].

Figures 6 and 7 display a sample of Turbulent Jet Ignition experimental results [7, 48] taken from the test engine used in this study. Results are shown for the reader to gauge some background information on the unconventional combustion system before displaying the results of the ignition energy study performed for this paper. It is noted that the jet ignition tests were completed using gasoline for the main chamber and a very small amount of propane for the pre-chamber as further outlined in the experimental setup. Results were obtained with typical ignition energy values.

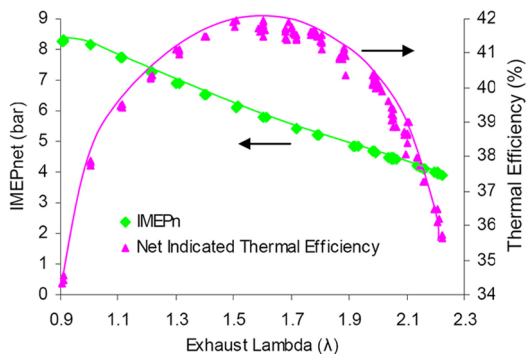


Figure 6. Turbulent Jet Ignition throttle-less (WOT) engine operation at 1500 rev/min and the subsequent effects on load and thermal efficiency with fuel variation in the single cylinder test engine, 10.4:1 CR.

Figure 6 displays the effects on load and thermal efficiency for throttle-less (unthrottled) Turbulent Jet Ignition operation, where load is controlled by varying the fuel addition in both combustion cavities. Additionally, Figure 7 makes a comparison to spark ignition combustion at the world wide mapping condition of 1500 rev/min, 3.3 bar IMEPn (~ 2.62 bar BMEP).

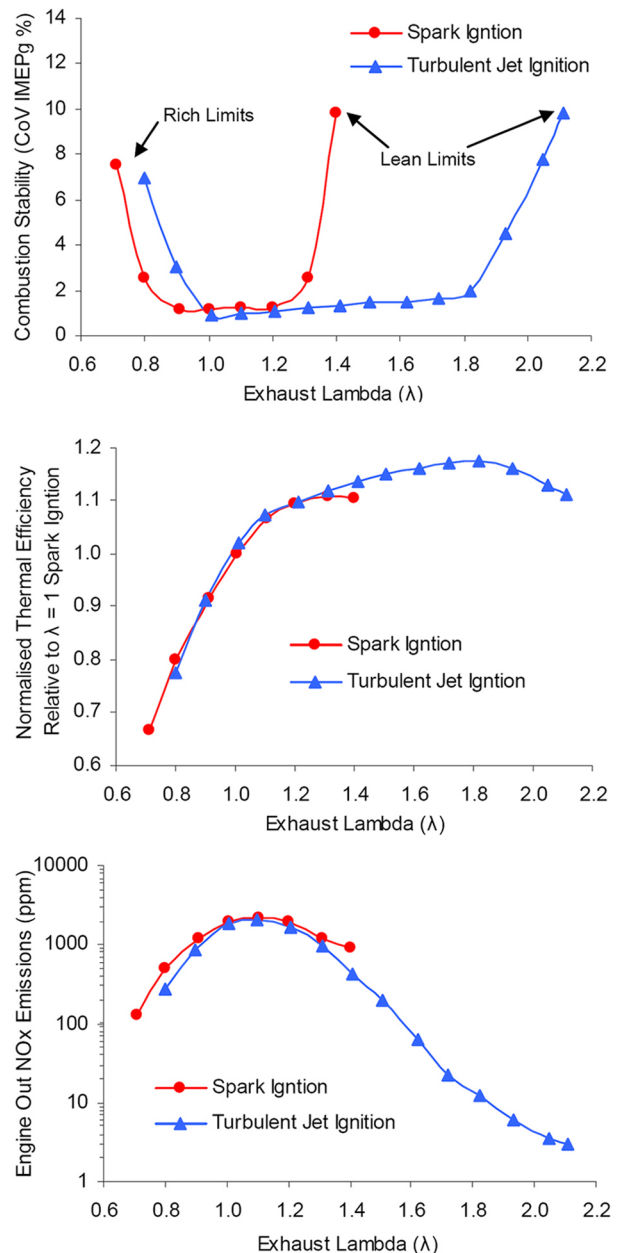


Figure 7. Comparison of spark ignition and jet ignition combustion systems with increased dilution levels (excess air or excess fuel with hot internal EGR: 30°CA NVO) up to the combustion stability limit ($<10\%$ CoV IMEPg). Constant speed/load world wide mapping condition of 1500 rev/min, 3.3 bar IMEPn (~ 2.62 bar BMEP).