

Knock Limit Extension with a Gasoline Fueled Pre-Chamber Jet Igniter in a Modern Vehicle Powertrain

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ABSTRACT

Turbulent Jet Ignition is an advanced spark initiated pre-chamber combustion system for otherwise standard spark ignition engines. Combustion in the main chamber is initiated by jets of partially combusted (reacting) pre-chamber products which provide a high energy ignition source. The resultant widely distributed ignition sites allow relatively small flame travel distances enabling short combustion durations and high burn rates. Demonstrated benefits include ultra lean operation ($\lambda > 2$) at part load and high load knock improvement.

This study compared the knock limit of conventional spark ignition and pre-chamber jet ignition combustion with reducing fuel quality in a modern PFI engine platform. Seven PRF blends ranging from 93-60 octane were experimentally tested in a stoichiometric normally aspirated single cylinder research engine at 1500 rev/min and ~WOT (98 kPa MAP). The majority of jet ignition experiments utilized an unfueled pre-chamber (no pre-chamber auxiliary fuel addition), with results highlighting significant knock limit extension with this combustion system. At MBT combustion phasing, a 10 octane number improvement was recorded with the unfueled pre-chamber over conventional spark ignition combustion due to the burn rate enhancement. At the combustion stability limit (3% CoV IMEPg) with spark retard, the unfueled pre-chamber jet igniter was capable of operating on 65 octane fuel, corresponding to a >15 octane number benefit due to the increased ignition delay and the ability to burn the main charge very late and very quickly. This is estimated to correspond to a base compression ratio increase of ~3 points over conventional spark ignition combustion at the 1500 rev/min test condition, in the same test engine. Additional experiments were also completed using an auxiliary fueled pre-chamber, with the PRF fuel fed into the pre-chamber cavity as well as the PFI main chamber. Results highlight further burn rate enhancement when fueling the pre-chamber independently of the main chamber, with successful WOT engine operation utilizing 60 octane fuel. Further experiments using standard US 87 (R+M)/2 pump fuel were completed up to 5500 rev/min and 13 bar IMEPn, with similar knock limit extensions observed with the pre-chamber jet igniter when compared to the baseline spark ignition combustion system.

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BACKGROUND

IGNITION ENHANCEMENT: PRE-CHAMBER COMBUSTION SYSTEMS

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]. Many variants of the pre-chamber combustion system have been developed [3], 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 [4] 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: a very small pre-chamber volume, small orifices connecting the main and pre-chamber combustion cavities and the option for auxiliary pre-chamber fueling. 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. 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 [5, 6, 7]. Further review of pre-chamber initiated combustion systems has been documented [3], with additional information on previous jet ignition research also available in the literature [3, 8, 9, 10, 11, 12].

A major advantage of the pre-chamber Turbulent Jet Ignition system presented in this paper 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). 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 [13, 14, 15].

KNOCK REDUCTION TECHNIQUES

Extending the knock limit for the spark ignited engine has been a challenge that engineers have faced since the inception of pre-mixed combustion systems. The effects of increasing the knock margin using varying techniques have been studied and documented in detail, with findings being compared to the extent that each technique is capable of lowering the octane number requirement (ONR) of the powertrain. [Table 1](#) summarizes the recent literature, highlighting and comparing the effects of various parameters on the ONR of an engine.

With the widespread introduction of mild levels of engine downsizing (~20 bar BMEP) into the marketplace across both Europe and North America, in-cylinder charge cooling through direct injection technology has been the recent enabling technology to allow the knock limits to be extended for viable production implementation. Additionally, extensive knock limit research has been completed on downsized platforms using diluent based strategies (excess air or cooled EGR [16, 17, 18]) to suppress auto-ignition in the end-gas regions of pre-mixed combustion systems. Although these diluent based concepts have been very successful in extending the knock limits, the increased dilution requirements place high demands on the powertrain air handling systems, and hence these systems require complex and expensive boosting systems to overcome the reduced engine performance and transient response.

One concept for knock mitigation for future powertrains surrounds ignition enhancement via the use of a distributed ignition system. This concept can be applied to both normally aspirated or boosted powertrains and relies on reducing the time the end-gas spends at elevated pressure and temperature (residence time) by burning the charge before auto-ignition can occur. There are many ways to achieve a distributed type of ignition system, examples being multiple spark plugs, corona or laser type ignition. However, the most successful distributed ignition concept to date has been the pre-chamber torch cells of the 1960's and 70's previously described. Although these past pre-chamber torch cells had knock limit success, research has been relatively non-existent in modern production platforms.

Table 1. Effect of various parameters on the octane number requirement (ONR) of a spark ignition engine [16, 19, 20, 21, 22, 23, 24, 25, 26].

Parameters	Octane Number Requirement (ONR)	Range Tested
Spark Advance	Increase 1 ONR / 1° knock limited spark advance	0 - 30° CA
Intake Air Temperature	Increase 1 ONR / 7°C	20 - 90°C
Air-Fuel Ratio (AFR)	Peaks around 5% rich of stoichiometric, Decreases 2 ONR / 0.1 λ	0.8 - 1.6 λ
Dilution: Cooled EGR	Decrease 3-4 ONR / 10% mass diluent	0 - 20% mass diluent
Manifold Absolute Pressure	Increase 3-4 ONR / 10 kPa	85 - 135 kPa
Compression Ratio	Increase 5 ONR / CR	5 - 12 CR
Exhaust Back Pressure	Increase 1 ONR / 30 kPa	0 - 65 kPa
Coolant Temperature	Increase 1 ONR / 10°C	70 - 110°C
Altitude	Decrease 1.4 ONR/300 m Decrease 2.5 ONR/300 m	0 - 1800m 1800 - 3600m
Humidity	Decrease 1 ONR when increasing relative humidity from 40% to 50% at 30°C	-
Engine Deposits	Increase 6-9 ONR over life of engine	0 - 250000km
Excessive Oil Consumption	Increase up to 12 ONR depending on driving style	-
Type of Fuel Injection	Decrease 4 ONR when DI used over PFI	-
Increasing Squish	Decrease up to 5 ONR as squish area increases	0 - 67% squish area
Combustion Chamber Shape	Decrease up to 15 ONR from cylindrical to modern type chamber	7.8 - 11 CR
Hydrogen (H ₂) Addition	Decrease 1 ONR / 1% H ₂ added	0 - 12% H ₂ added

OBJECTIVES

The specific objectives of this paper are to:

- Quantify the knock limit extension at MBT (optimal combustion phasing) and at maximum spark retard (3% CoV IMEPg) when utilizing a pre-chamber jet igniter when compared to the baseline (conventional spark ignition combustion) in a modern engine platform.
- Investigate the knock limit effects of fueling the pre-chamber independently of the main chamber (e.g. with and without pre-chamber auxiliary fuel addition).

- Compare the performance between Turbulent Jet Ignition and the baseline conventional spark ignition combustion system with reducing fuel octane.

- Compare combustion burn parameters between Turbulent Jet Ignition and the baseline conventional spark ignition combustion system with reducing fuel octane.

- Determine the minimum fuel octane requirements at WOT for Turbulent Jet Ignition and the baseline conventional spark ignition combustion system in the same modern test engine.

TURBULENT JET IGNITION SYSTEM

The Turbulent Jet Ignition system [8, 10, 12, 27, 28, 29] (Figure 1, Figure 2, Figure 3) builds on previous pre-chamber research [3, 29, 30, 31], with the objective of making the technology more viable in current level production powertrains. The system applies off the shelf hardware and modern control systems to a robust pre-chamber design. Additionally, the system has been developed to operate on readily available commercial fuels (gasoline, propane, natural gas), overcoming previous pre-chamber jet igniter complications of using hydrogen as the pre-chamber [32, 33, 34, 35, 36, 37]. The system was initially developed as a simple spark plug replacement in a modern spark ignition combustion system.

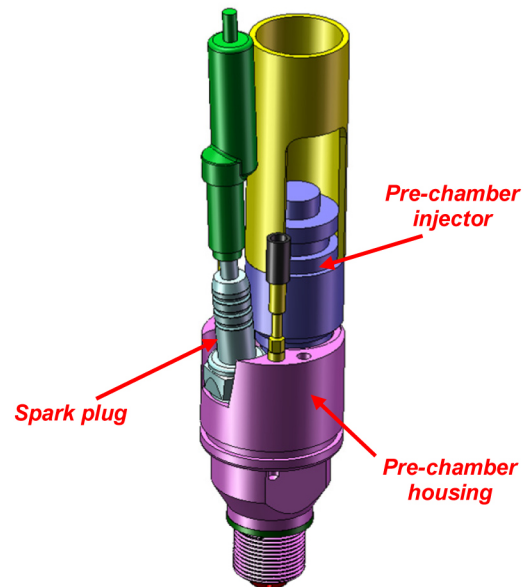


Figure 1. Design image of the Turbulent Jet Igniter, designed to replace the spark plug in a contemporary spark ignition combustion system.

The list below highlights some of the novel and defining features of the 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 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 fueled 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 fueled 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

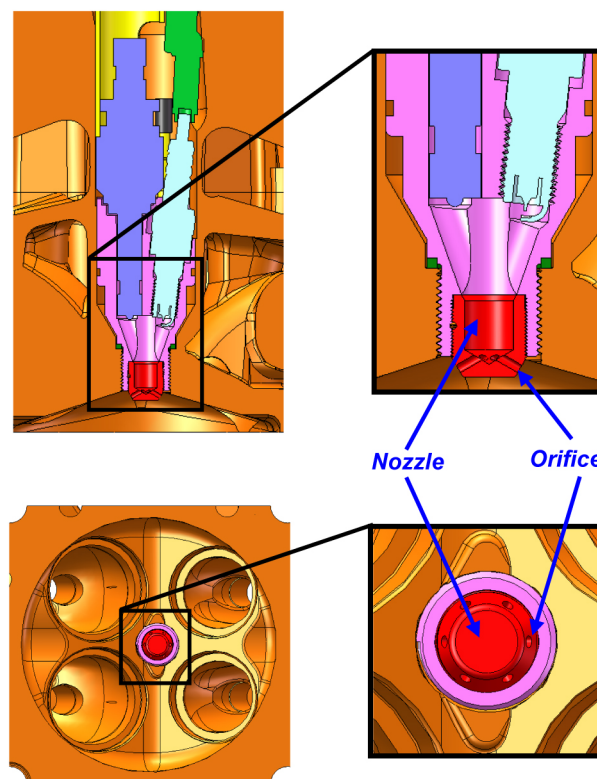


Figure 3. Design image highlighting the Turbulent Jet Ignition pre-chamber and nozzle in the 4-valve pent roof combustion system.

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 4](#). 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. Combustion initiation for both spark ignition and jet ignition systems was achieved using a spark plug and a conventional inductive ignition system, with 40 mJ of ignition energy. [Table 2](#) lists test engine specifications.

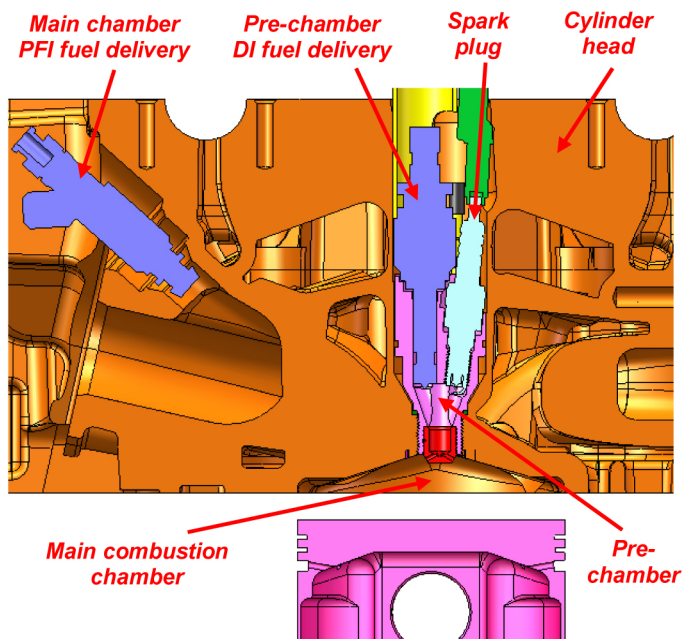
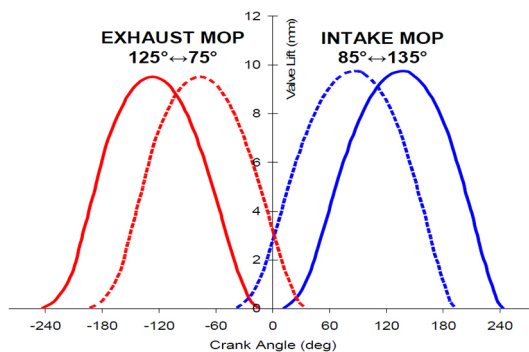


Figure 2. Section view highlighting the Turbulent Jet Igniter centrally installed in the test engine's four valve, pent roof combustion system.

Table 2. Test engine specifications.

TYPE	Normally aspirated single cylinder, 4 stroke, liquid-cooled, aluminum structure
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	<i>Spark Ignition:</i> PFI <i>Jet Ignition:</i> main chamber PFI pre-chamber DI (optional)
SPARK INITIATION	Inductive ignition, 40 mJ

**Figure 4. Range of intake and exhaust valve events with continuously variable camshaft phasers.**

OPERATING CONDITIONS

Table 3 summarizes the test operating conditions across both ignition systems. All experiments were completed at a fixed speed of 1500 rev/min, with this speed chosen due to the low speed high knock propensity. Reductions in fuel quality were achieved using PRF splash blends of Iso-octane and n-Heptane. Great care was taken to ensure very accurate blending ratios and to avoid any cross contamination with the varying fuels. Both the baseline spark ignition and pre-chamber jet ignition systems were evaluated on a back to back basis using the same PRF blend to ensure accurate comparisons, starting at the highest octane number. Hence, both ignition systems were evaluated within a day of each other at each PRF blend tested. All experiments were completed at stoichiometric conditions, with lambda (λ) values determined by analyzing the exhaust gas using computation (chemical balance of exhaust products) and confirmed directly with a wideband oxygen sensor. To avoid the effects of barometric pressure fluctuations, the intake

manifold absolute pressure (MAP) was set to 98 kPa as per SAE J1349 standards. Additionally, the intake and exhaust cam phasers were optimized for maximum IMEP_n at these conditions, which equated to high valve overlap. The valve events were then kept constant across all experiments. To ensure data consistency, the dynamometer test rig regulated coolant out, oil and intake air temperatures to set limits. Table 3 summarizes the operating conditions across experiments.

Table 3. Experimental operating conditions.

	Spark Ignition (Baseline)	Pre-Chamber Jet Ignition
Engine Speed	1500 rev/min	
Fuel Octane	PRF 93, 87, 80	PRF 93, 87, 80, 75, 70, 65, 60
Air-Fuel Ratio	$\lambda = \phi = 1$	
Intake Manifold Pressure	Set 98 kPa (~WOT), SAE J1349	
Water Temperature	88 - 90 °C	
Oil Temperature	85 ± 0.5 °C	
Air Temperature	28 - 29 °C	
Relative Humidity	28 - 30 %	
Cam Position	“Optimized Power Position” Fixed at high valve overlap	
Spark Timing	Advance: MBT or knock limited timing Retard: Stability limited 3% CoV IMEP _g	
Maximum Knock Limit Allowable	10-15 bar maximum knock amplitude (Audible Limit)	

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. 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 TDC probe. To ensure high data integrity, a new pressure transducer was utilized for these experiments with regular in-house deadweight test calibration. The testing strategy for each ignition system at each PRF blend involved finding the maximum spark advance, and then retarding the ignition in 2° crank angle (CA) increments until the combustion stability limit (3% CoV IMEP_g) was reached. The engine was left to stabilize for 5 minutes before moving onto the next ignition setting and the maximum knock amplitude recorded in this time period. The knock amplitude was computed using A&D's CAS system routine, which is a filtered pressure trace.