

A Gasoline Fueled Pre-Chamber Jet Ignition Combustion System at Unthrottled Conditions

William P. Attard and Hugh Blaxill
MAHLE Powertrain

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 near stoichiometric conditions.

Although previous results of this combustion system have been very promising, the main hurdle of this system has been the need for a 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 robustly using a sole gasoline system, with vaporized gasoline found to be a successful substitute for the pre-chamber propane over all comparable conditions. With this concept, the test engine recorded a peak net thermal efficiency of 42.8% (190 g/kWh ISFCn) and single digit engine out NOx emissions. The pre-chamber jet ignition system was also examined at unthrottled stoichiometric conditions up to 5500 rev/min, with successful operation demonstrated up to 13.2 bar IMEPn. Additionally, jet ignition combustion was also examined in order to evaluate pressure rise rate limitations for potential future high load powertrain applications.

CITATION: Attard, W. and Blaxill, H., "A Gasoline Fueled Pre-Chamber Jet Ignition Combustion System at Unthrottled Conditions," *SAE Int. J. Engines* 5(2):2012, doi:10.4271/2012-01-0386.

JET IGNITION BACKGROUND

The Turbulent Jet Ignition system [1, 2, 3, 4, 5, 6, 7, 8, 9] presented in this paper builds on previous pre-chamber jet igniter research [10, 11, 12], with the objective of making the technology 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 fuel [13, 14, 15, 16, 17, 18]. The system was initially developed as a simple spark plug replacement in a modern spark ignition combustion system. Unique features of this particular pre-chamber have been well documented [6, 8], which include a very small pre-chamber volume, small orifices connecting both combustion cavities, a dedicated pre-chamber fuel supply (auxiliary fueling) and a spark plug combustion trigger to allow phasing control. Previous publications have also described the calibration and control strategy [5, 6, 7, 8]. Furthermore, experimental results have highlighted high thermal efficiency

(42%), significant fuel economy improvement (>20%), high load capability (>10 bar IMEP), and near zero engine out NOx emissions (< 10 ppm) in a standard contemporary PFI engine platform [1, 2, 3, 4, 5, 6, 7, 8, 9]. Figure 1 and Figure 2 display computer design images of the pre-chamber installed in the test engine's 4-valve pent roof combustion system.

OBJECTIVES

The specific objectives of this paper are to:

- Investigate the suitability of a lean burn gasoline fueled jet ignition combustion system using vaporized gasoline as the pre-chamber fuel at unthrottled conditions.
- Determine maximum levels of diluent while still maintaining adequate combustion stability (5% CoV IMEPg).
- Compare the thermal efficiency, emissions and combustion burn parameters between the varying fueled jet ignition systems and conventional spark ignition combustion with increasing levels of excess air diluent.

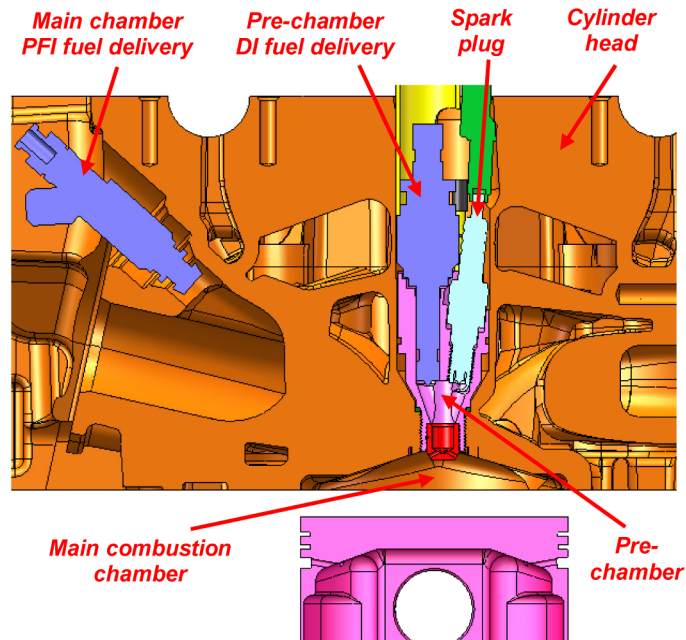


Figure 1. Section view highlighting the Turbulent Jet Igniter centrally installed in the test engine's four valve, pent roof combustion system.

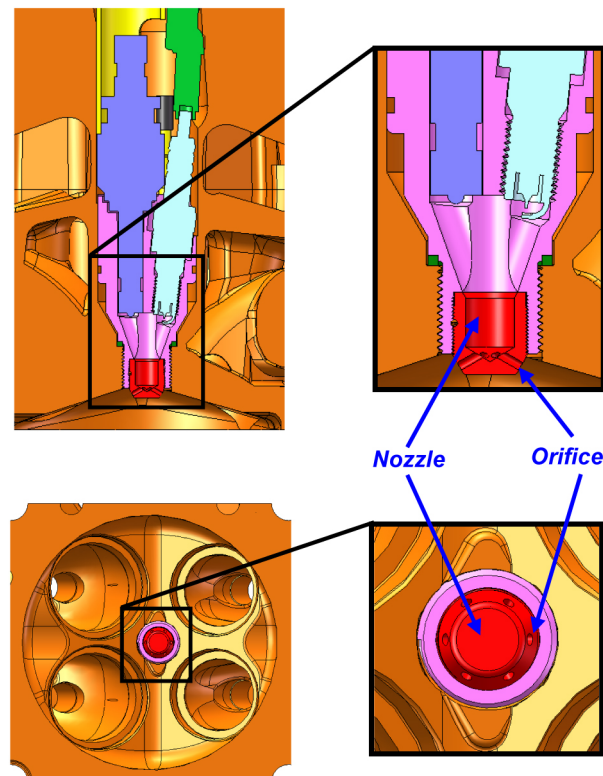


Figure 2. Design image highlighting the Turbulent Jet Ignition pre-chamber and nozzle in the 4-valve pent roof combustion system.

- Investigate the suitability of a stoichiometric gasoline fueled jet ignition combustion system at high engine speeds (5500 rev/min) and loads (13.2 bar IMEPn).

- Examine jet ignition pressure rise rates at stoichiometric unthrottled conditions and evaluate varying combustion tuning techniques in order to limit pressure rise rates.

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 3](#). 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.

Table 1. 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

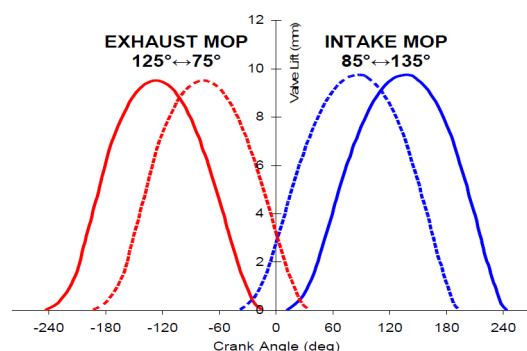


Figure 3. Range of intake and exhaust valve events with continuously variable camshaft phasers.

All experiments completed for this paper utilized regulated gasoline (EEE Indolene) with a 93 (R+M)/2 Anti-Knock Index (AKI). However, engine fuel delivery systems varied between spark ignition and jet ignition systems due to the addition of the pre-chamber fuel event. Spark ignition combustion experiments utilized port fuel injection (PFI) at standard production fuel pressures (4 bar). However, jet ignition tests utilized port fuel injection for the main chamber while small amounts of vaporized gasoline were directly injected into the pre-chamber in gaseous form at low pressure (4 bar). The gasoline fuel vaporizer used in experiments for the pre-chamber was developed internally and simply integrated into the gasoline fuel system. This ensured the on-demand fuel vaporizer was continually fed a consistent gasoline fuel blend as required, with [Figure 4](#) displaying a schematic of the complete jet ignition gasoline fuel system. The fuel vaporizer utilized a PID controlled heating element with a 120V AC mains power supply. The PID controlled the fuel supply to levels above the saturation temperature to ensure only vapor was supplied. Additionally, the heating system was positioned accordingly to avoid the vaporized fuel changing back to liquid phase as it entered the pre-chamber direct injector. The small amount of external electrical energy used to power the fuel vaporizer is not considered in the efficiency calculations. The initial purpose of examining vaporized gasoline as a pre-chamber fuel was to determine whether shortcomings with liquid gasoline [2, 3] could be attributed to the poor mixture preparation inside the small cavity or fuel properties of the dual fuel system (gasoline - propane). However, experimental results have highlight the benefits of using a heated fuel supply for the pre-chamber, possibly providing some validation for a heated tip pre-chamber direct injector.

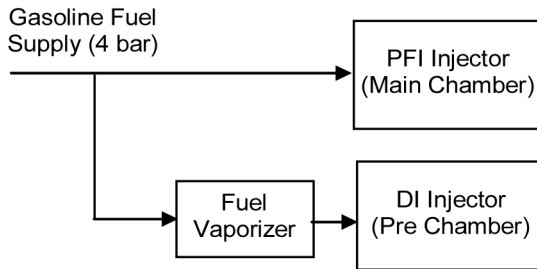


Figure 4. Gasoline fuel system used for pre-chamber experiments, noting the in-house developed gasoline fuel vaporizer for the pre-chamber fuel supply.

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 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 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.

EXPERIMENTAL RESULTS

UNTHROTTLED LEAN OPERATION

Figure 5, Figure 6, Figure 7 displays single cylinder performance, efficiency, emissions and combustion comparisons of spark ignition and jet ignition systems for unthrottled (~ 98 kPa MAP) conditions at 1500 rev/min. The baseline spark ignition combustion system is compared to the new sole gasoline jet ignition system (gasoline - vaporized gasoline) with the previous dual fuel (gasoline - propane) jet ignition results also displayed for reference. It is noted that the load is altered at unthrottled conditions due to dilution level variation (excess air or excess fuel with hot internal EGR) up to the combustion stability limit, which is defined to be less than 5% CoV IMEPg for this study. Both the intake and exhaust camshafts have been left in the parked OEM

positions to retain a maximum amount of hot internal residual, corresponding to slightly negative valve overlap.

The upper graph of Figure 5 shows an unthrottled comparison of IMEPn with jet ignition and spark ignition combustion. Results show matched peak performance and similar trends between all combustion systems, with load decreasing for increasing levels of dilution. For clarity, the load data presented in this graph is also displayed as a secondary x-axis (grey) in the remaining experimental results of this section. Lean limit results from the middle diagram of Figure 5 highlight that the sole gasoline jet ignition system (gasoline - vaporized gasoline) has the ability to significantly extend the excess air dilution rates when compared to conventional spark ignition combustion. A lean limit exhaust lambda of 2.12 was observed at this operating condition for the sole gasoline (gasoline - vaporized gasoline) jet ignition case. This compares to a lambda of 2.09 for the dual fuel (gasoline - propane) jet ignition system. The slight extension in the lean limit with the vaporized gasoline system is attributed to the elevated pre-chamber fuel supply. The higher pre-chamber fuel temperatures have improved the pre-chamber combustion, which has in turn improved the main chamber combustion.

Additionally from the lower graph of Figure 5, the peak thermal efficiency of the sole gasoline (gasoline - vaporized gasoline) jet ignition system is significantly improved when compared to conventional spark ignition combustion. At this operating point, a peak net indicated thermal efficiency of 41.9% (194 g/kWh ISFCn) is recorded in the 5-6 bar IMEPn region using a contemporary PFI production engine, with a relatively low CR of 10.4. This equates to an 11% relative efficiency improvement when compared to stoichiometric spark ignition combustion in the same test engine using the same fuel. Peak efficiency results from the sole gasoline jet ignition system are identical (within the realms of experimental error) to the dual fuel (gasoline - propane) system, which recorded 42% in the same load region. Peak efficiency gains for the jet ignition combustion system across all fuels tested are attributed to a combination of combustion improvements associated with the distributed ignition system, reduced heat losses, changes in the specific heat ratio and the near elimination of dissociation associated with low combustion temperatures.

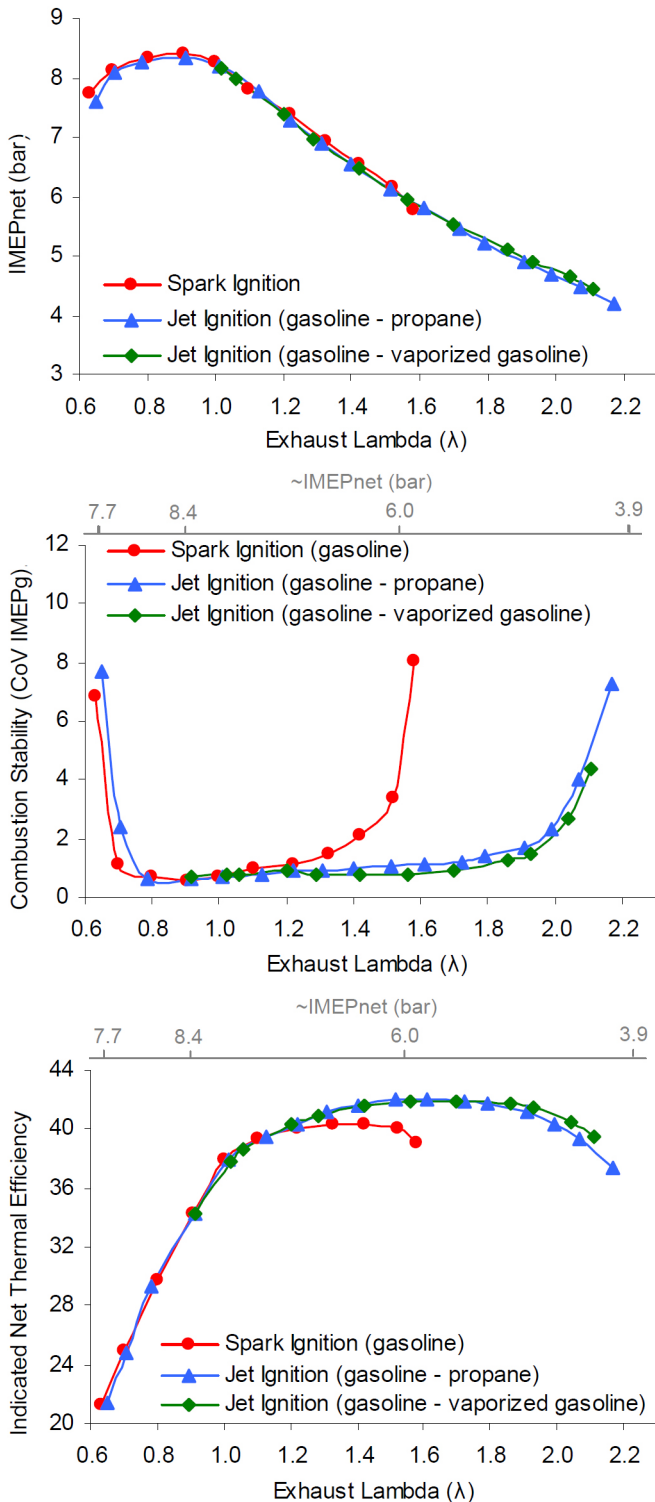


Figure 5. IMEP and thermal efficiency comparisons of spark ignition (gasoline), jet ignition dual fuel (gasoline - propane) and jet ignition sole fuel (gasoline - vaporized gasoline) combustion systems. 1500 rev/min, unthrottled (~ 98 kPa MAP), varying load due to dilution variations, (main chamber fuel - pre chamber fuel).

Further examining the overall efficiency in Figure 5, results highlight that the vaporized gasoline (gasoline - vaporized gasoline) has some slight advantages when compared to the dual fuel (gasoline - propane) results. Past lambda ~ 1.8 up to the lean combustion stability limit, the vaporized gasoline system has higher net efficiency also corresponding to slight combustion stability improvements as highlighted by the CoV IMEPg in the middle graph of Figure 5. The efficiency improvement with the vaporized gasoline system is also attributed to the elevated pre-chamber fuel supply temperatures and associated improved pre-chamber combustion due to the heated vaporized fuel supply. This effect is more evident near the combustion stability limit as higher proportions of pre-chamber fuel are required to support stable combustion. Hence, the newly developed sole gasoline jet ignition system using liquid gasoline for the main chamber and vaporized gasoline for the pre-chamber can match the dual fuel system, with additional efficiency improvements near lambda 2 due to slight improvements in the lean limit associated with the improved pre-chamber combustion.

Figure 6 displays engine out emission comparisons between all systems. When comparing spark ignition to jet ignition combustion, one of the main advantages of running very high levels of excess air is very low engine out NOx emissions due to the lower peak combustion temperatures. Hence, for both dual fuel and sole fuel systems, jet ignition NOx emissions are reduced to almost zero levels (<10 ppm). However, some slight differences in NOx emissions are observed between the single fuel (gasoline - vaporized gasoline) and dual fuel (gasoline - propane) jet ignition systems as examined in the lower diagram of Figure 6. For equivalent excess air dilution (equivalent lambda), NOx emissions are slightly higher with the sole gasoline jet ignition system. The main reason for the higher NOx emissions is related to the vaporized gasoline pre-chamber direct injection event and resulting pre-chamber combustion. The elevated fuel supply temperature for the pre-chamber when using vaporized gasoline over propane has resulted in hotter pre-chamber combustion, leading to marginally higher levels of pre-chamber sourced NOx emissions. This effect is magnified as the excess air dilution is increased and hence more pre-chamber fuel addition is required to support stable combustion. Nevertheless, NOx emission levels are still on the same magnitude and comparable to the dual fuel system, overcoming the previous results recorded with the liquid gasoline fueled pre-chamber [2, 3]. Results also confirm the previous findings from the liquid fueled pre-chamber experiments in that the reductions in lean limit and increases in NOx emissions were not related to the fuel, rather the non-optimal pre-chamber mixture preparation due to hardware limitations associated with the modified off-the-shelf pre-chamber direct injector.