

Visualization of Propane and Natural Gas Spark Ignition and Turbulent Jet Ignition Combustion

Elisa Toulson, Andrew Huisjen, Xuefei Chen, Cody Squibb, Guoming Zhu and Harold Schock
Michigan State University

William P. Attard
MAHLE Powertrain LLC

ABSTRACT

This study focuses on the combustion visualization of spark ignition combustion in an optical single cylinder engine using natural gas and propane at several air to fuel ratios and speed-load operating points. Propane and natural gas fuels were compared as they are the most promising gaseous alternative fuels for reciprocating powertrains, with both fuels beginning to find wide market penetration on the fleet level across many regions of the world. Additionally, when compared to gasoline, these gaseous fuels are affordable, have high knock resistance and relatively low carbon content and they do not suffer from the complex re-fueling and storage problems associated with hydrogen. Although both propane and natural gas offer unique lean burn benefits for spark ignition combustion, a novel Turbulent Jet Ignition pre-chamber system was also evaluated, with several Turbulent Jet Ignition optical images compared to the spark ignition images in order to provide insight into the lean limit extension provided by the pre-chamber combustion system. 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 results from the partially combusted (reacting) pre-chamber products initiating combustion in the main chamber. The distributed ignition sites enable relatively small flame travel distances enabling short combustion durations and ultra lean engine operation exceeding λ 2. Experimental findings from the spark ignition study highlight faster flame propagation with propane when compared to natural gas across all speed load points tested. However, across all fuels, the optical images revealed rapid spark ignition combustion deterioration with lean engine operation exceeding λ 1.4. When comparing ignition systems, the Turbulent Jet Ignition pre-chamber system demonstrated significant benefits relative to the spark ignition system, with the optical images revealing stable combustion past λ 1.8 resulting in the near elimination of NOx emissions in-cylinder and significant improvements in efficiency and fuel economy.

CITATION: Toulson, E., Huisjen, A., Chen, X., Squibb, C. et al., "Visualization of Propane and Natural Gas Spark Ignition and Turbulent Jet Ignition Combustion," *SAE Int. J. Engines* 5(4):2012, doi:10.4271/2012-32-0002.

INTRODUCTION AND BACKGROUND

In recent years there has been renewed interest in lean burn technologies, primarily due to the improvement in fuel efficiency that these technologies can provide [1,2,3]. Lean burn occurs when fuel is burnt in excess air and running an engine in this manner has many advantages over conventional stoichiometric combustion. One advantage of running lean occurs as the introduction of additional air increases the specific heat ratio, which leads to an increase in thermal efficiency. Additionally, lean engine operation reduces pumping losses for a given road load by tending towards

throttle-less operation, which can further improve drive-cycle fuel economy. In this case, power output can be somewhat controlled by varying the fuel supplied to the combustion chamber (as in a diesel engine) rather than by throttling, as is done in conventional stoichiometric spark ignition engines. Lean burn technology has not been extensively implemented for several reasons including compromised combustion stability and three-way catalyst incompatibility. In addition, although NOx emissions decrease at higher λ due to lower combustion temperatures, significant improvements in NOx emissions can only begin to be seen at the lean limit ($\lambda \sim 1.4$) of conventional spark ignition engines. Moreover, the effectiveness of the three-way catalyst, which is the primary

means to control NO_x, HC and CO emissions in conventional spark ignition engines, degrades rapidly at AFR that vary from stoichiometric.

There are also several other disadvantages of lean burn technology that have prevented it from being more widely used. The narrow flammability limits of most fuels make it difficult to run lean while maintaining adequate combustion stability with low misfire rates. Poor combustion stability leads to increased HC and CO emissions due to misfire and partial burning cycles. Partial burning is primarily caused by the slower laminar flame speeds of lean mixtures that severely affect flame kernel growth and hence flame propagation. Furthermore, as the lean limit of combustion is approached, irregular ignition and HC emissions increase while power output substantially decreases. The laminar flame speed of natural gas is lower than that of other hydrocarbon fuels, including propane, due to its higher activation energy and this effect is most significant under lean conditions [4]. To compensate for the lower laminar burning velocity of lean mixtures, it is necessary to increase the in-cylinder charge motion or charge density to attain a sufficiently rapid burn rate. One method that overcomes the negative effects of lean combustion is ignition enhancement using Turbulent Jet Ignition, which utilizes a pre-chamber combustion initiation system [5,6,7,8]. The Turbulent Jet Ignition concept involves the use of a chemically active, turbulent jet to initiate combustion in lean fuel mixtures. With jet ignition, the combustion of the main charge is reliable over a much broader range of air-fuel ratios since the jet acts as a distributed ignition source. The large number of distributed ignition sites ensures that the flame travel distances are relatively small enabling short combustion durations even in traditionally slow burning lean mixtures [9, 10]. Additionally, the combusting jet provides an ongoing combustion and jet motion of substantial mass of fuel-air mixture, which enables combustion in diluted mixtures and benefits efficiency. Peak thermal efficiency improvements with Turbulent Jet Ignition over baseline SI systems with very lean mixtures have been shown to be in the range of 20% due to the improved combustion process, near elimination of dissociation due to the low combustion temperatures, and reduced engine throttling and heat losses [11, 12].

OBJECTIVE

The objective of this research is to examine and analyze natural gas and propane combustion in an optically accessible engine. The specific objectives of this paper are to:

- Examine propane and natural gas spark ignition combustion at several air to fuel ratios and speed-load operating points
- Compare the baseline propane and natural gas spark ignition and pre-chamber Turbulent Jet Ignition combustion systems at the world-wide mapping point of 1500 rev/min, 3.3 bar IMEP_n (~2.62 bar BMEP)

- Compare the characteristics of Turbulent Jet Ignition and spark ignition combustion

EXPERIMENTAL SETUP

Optical Engine Assembly

The normally aspirated optical single-cylinder research engine used in experiments was assembled collaboratively between Michigan State University (MSU) and MAHLE Powertrain. The bottom end utilized a MSU modified Hatz platform [13] with a Bowditch arrangement allowing optical combustion visualization through a quartz window (58 mm diameter) in the piston crown [14]. The 0.4 liter single-cylinder engine featured a flat top piston crown in a modern pent roof combustion system. The top end assembly consisted of a modified single-cylinder version of MAHLE Powertrain's DI-3 cylinder head [15] which incorporated double overhead camshafts and four valves per cylinder. The cylinder head was originally designed to incorporate central spray guided direct injection, however the combustion system was modified to accept PFI and hence allow the pre-chamber jet igniter to be packaged centrally in the combustion system. Standard production intake and exhaust camshaft profiles were utilized. 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. Table 1 lists the optical engine specifications while Figure 1 displays a computer design image section view through the assembly. Figures 2 and 3 display the test rig and optical view of the combustion chamber, with the 58 mm diameter

Table 1. Test engine specifications

TYPE	Normally aspirated single cylinder, 4 stroke, liquid-cooled, aluminum head/block
OPTICAL IMAGING	Bowditch piston with 58 mm diameter quartz window in piston crown
DISPLACEMENT	0.4 liter
BORE x STROKE	83 x 73.9 mm
COMPRESSION RATIO	10:1
COMBUSTION CHAMBER	Pent roof, central ignition
VALVE ACTUATION	4-valve, DOHC
INTAKE	500 mm runner length, 12 liter plenum volume
EXHAUST	300 mm runner length, 12 liter plenum volume
FUEL DELIVERY	Spark Ignition: PFI Jet Ignition: main chamber PFI pre-chamber DI
SPARK INITIATION	Inductive ignition system (35 mJ), ionization detection

quartz window in the piston crown enabling a high portion of the combustion chamber to be viewed in the 83 mm bore.

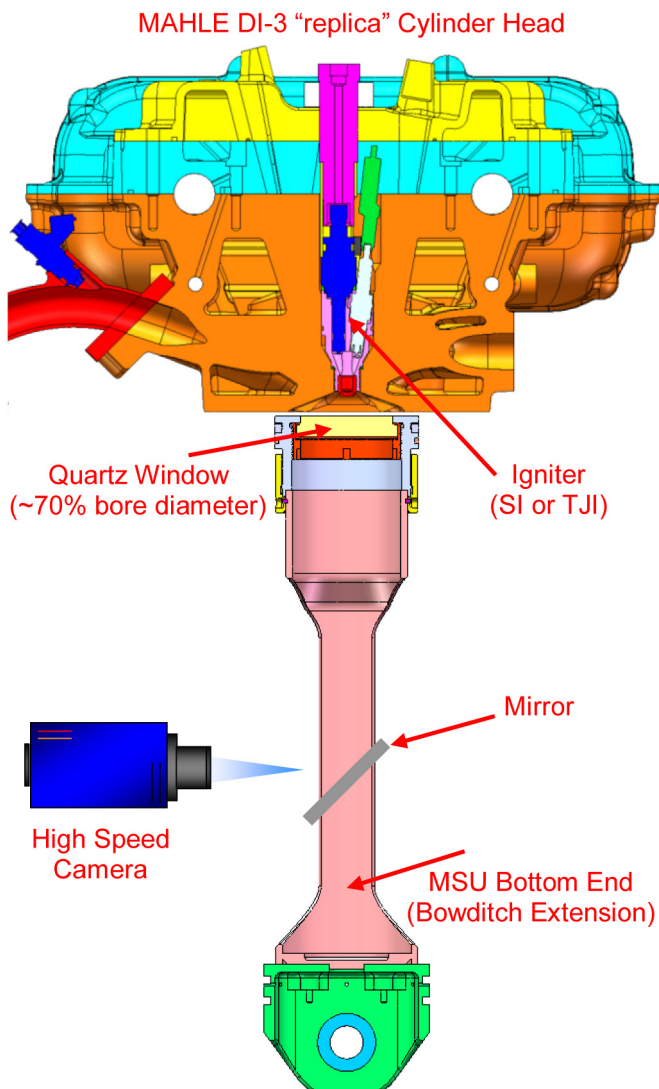


Figure 1. Computer design image section view through the assembly.

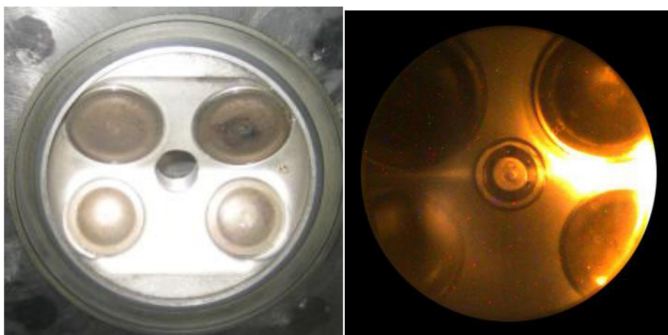
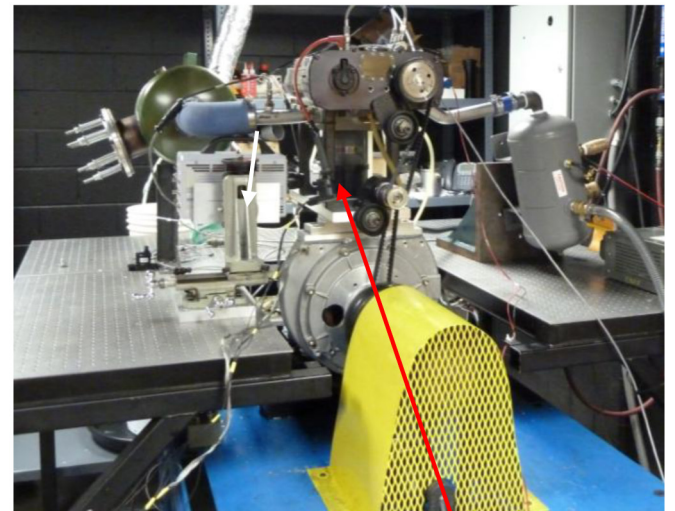


Figure 2. View of combustion chamber prior to installation (Left) and through the Bowditch extended piston with 58 mm diameter quartz insert (Right).



High Speed Camera

MSU Bottom End (Bowditch Extension)

MAHLE DI-3 "replica" Cylinder Head

Port Fuel Injector

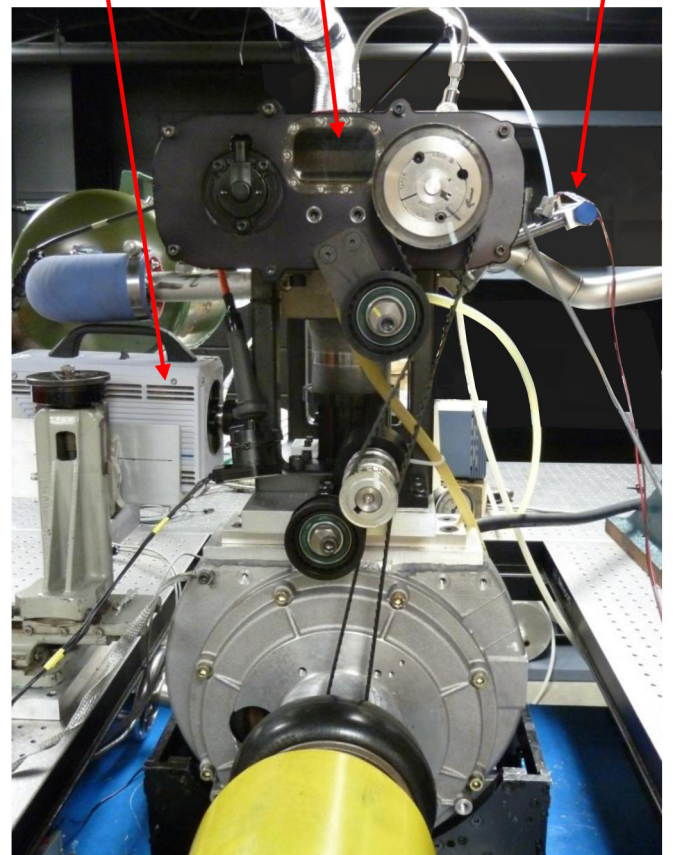


Figure 3. Experimental engine setup.

Due to the optical arrangement of the test rig, engine firing experiments were limited to 50 cycle sequences due to optical limitations and combustion image quality degradation.

To ensure consistency, the cooling and lubrication (oil pressure and scavenge) systems were de-coupled from the crankshaft and externally operated. This allowed the barrel and cylinder head to be pre-heated to 90°C prior to firing experiments and ensured lubrication integrity under the increased inertia loading from the Bowditch extended piston design.

Table 2. Gaseous fuel properties compared to gasoline
[16,17,18,19,20].

	Natural Gas (~Methane CH ₄)	Propane (C ₃ H ₈)	Gasoline
Molecular Weight	~18	44.10	~110
Energy Density (MJ/kg)	45	46.4	44.0
Energy Density (kJ/mol)	810	2002	4840
Stoichiometric AFR (by mass)	14.5	15.7	14.6
Stoichiometric AFR (by volume)	9.04	23.9	57.7
Energy in 1 mol Stoichiometric Fuel-Air Mixture	80.8	80.4	82.5
Gas Constant – R (kJ/kg K)	0.518	0.187	–
Density (kg/m ³) 0 °C and 1 atm	0.79	2.0	735
Laminar Flame Speed (m/s)	0.39	0.45	0.4
LFL (%) (by vol)	5.6	2.2	1.4
UFL (%) (by vol)	15	9.5	7.6
Lambda at LFL	1.9	1.9	1.2
Lambda at UFL	0.63	0.40	0.21
Auto Ignition Temperature (°C)	632	500	530
Min Ignition Energy (mJ)	0.33	0.30	0.8
Fuel Octane Rating (RON)	120	112	92-98
Fuel Octane Rating (MON)	120	97	80-90

The test rig measured gaseous fuel consumption on a mass basis directly using two inline thermal mass flow meters to ensure fuel consumption data integrity. Increased fuel rail volumes minimized the fuel flow pulsations experienced at the flow meters as a result of the single cylinder fuel injection configuration. All exhaust lambda (λ) values presented in this paper were obtained using a heated wideband oxygen sensor fitted in the exhaust runner. Hence for the jet ignition system, the exhaust lambda is inclusive of both the main and pre-chamber fuel. A flush mounted Kistler 6052A pressure transducer was used to measure in-cylinder pressure, with TDC alignment confirmed by interpreting motored log

pressure-volume data. 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. The combustion imaging was accomplished with a non-intensified high speed digital video camera (Photron, Model Fastcam APX RS) which was triggered by the rising edge of the spark signal. The camera was set to record at 10,000 images per second with a resolution of 512 pixels by 512 pixels to cover a spatial imaging area of approximately 120 mm by 120 mm. Table 2 compares the gaseous fuel properties of both natural gas and propane to gasoline in order for the reader to gauge fuel differences between liquid and gaseous applications.

Fuel Injection and Ignition Systems

The optical test engine was designed to be equipped with either a conventional spark plug or a pre-chamber Turbulent Jet Igniter [5, 6, 11, 21] with the same cylinder head used for both systems. Figure 4 displays a computer generated image of the Jet Igniter which simply replaces the 14 mm spark plug used in the conventional spark ignition combustion system. Figure 5 displays further images of both ignition systems installed in the test engine's cylinder head. Extensive metal engine research has been completed with this specific pre-chamber Turbulent Jet Igniter, with experimental results of the system published in the literature [6, 11, 21, 22].

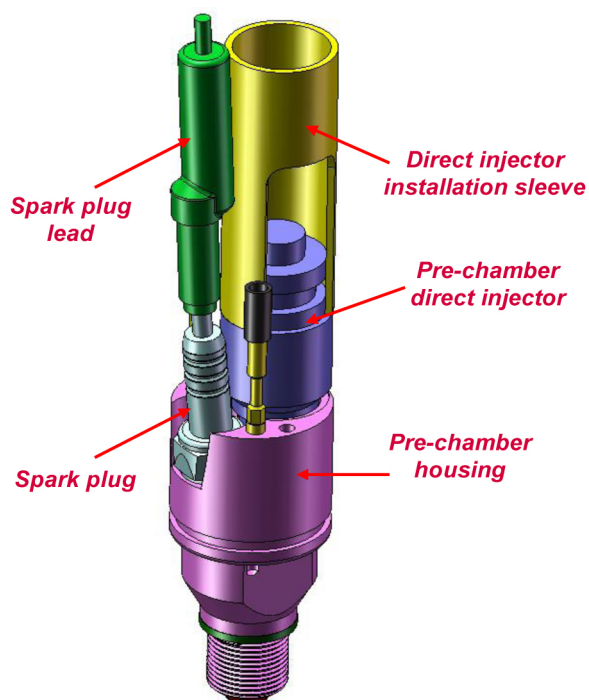


Figure 4. Design image of the Turbulent Jet Igniter, designed to replace the spark plug in a contemporary spark ignition combustion system.

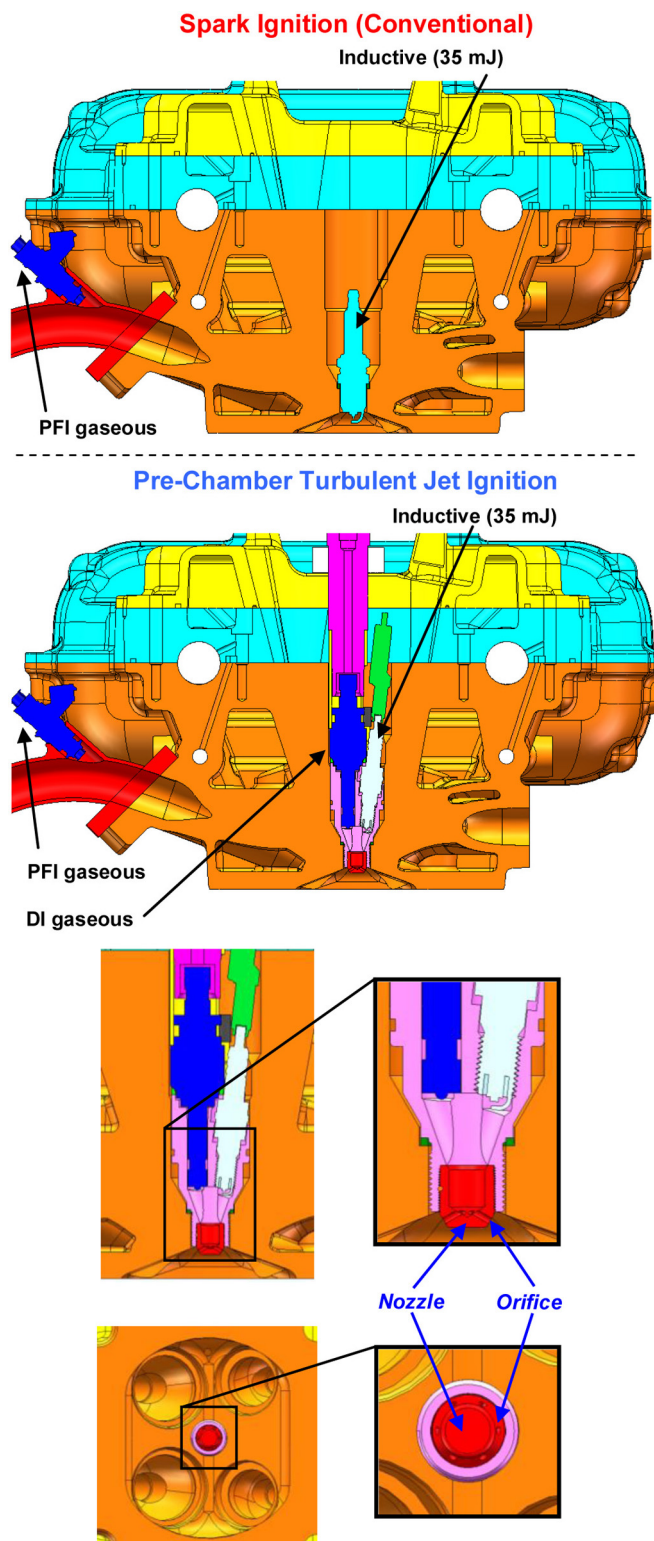


Figure 5. Spark ignition and Pre-Chamber Turbulent Jet Ignition combustion systems.

Combustion initiation for both spark ignition and jet ignition combustion systems was achieved using a spark plug and an inductive ignition system (35 mJ). The inductive

ignition system also incorporated a MSU developed ionization detection system for further combustion diagnostics, with the ionization detection electronics integrated into the ignition coil spark plug assembly.

Due to the varying ignition systems and the need to supply the pre-chamber with auxiliary fueling, fuel delivery systems varied between spark ignition and jet ignition systems due to the addition of the pre-chamber fuel event. Both ignition systems utilized a Bosch gaseous NGI-2 PFI injector which port injected gaseous fuel at relatively low fuel pressure. However, jet ignition tests also utilized small amounts of auxiliary fuel when running excess air dilution which allowed adequate pre-chamber combustion. Hence for jet ignition tests, the bulk of fuel energy was port fuel injected into the main chamber while the additional auxiliary fuel was directly injected into the pre-chamber. To minimize the complexity of the fuel system, the jet ignition system PFI and DI injectors shared a common fuel rail and hence single gaseous fuel.

BASELINE RESULTS

Extensive metal engine experiments have previously been completed with the Turbulent Jet Ignition combustion system described in this paper [5, 6, 11, 12, 21,22,23,24]. Experiments were completed in a similar modern 4 valve single cylinder test engine, with the addition of wide angle camshaft phasers to control both the intake and exhaust valve events. A summary of the unthrottled thermal efficiency together with the part load fuel economy and NO_x emission benefits when comparing stoichiometric spark ignition (optimized valve events with camshaft phasers) and jet ignition combustion in the same test engine is given in Figure 6 [12, 24]. Figure 7 shows a comparison of spark ignition and jet ignition combustion at a part load operating condition of 1500 rev/min, 4.7 bar IMEP_n [24]. Obvious is the significant lean limit extension with jet ignition combustion, with stable engine operation near $\lambda = 2$ compared to only $\lambda = 1.4$ for conventional spark ignition combustion.

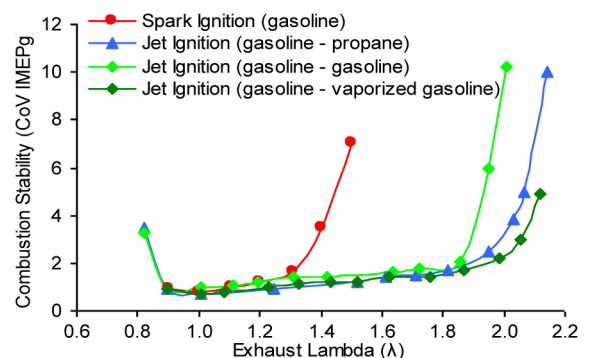


Figure 7. Spark ignition and Turbulent Jet Ignition combustion systems with varying dilution. 1500 rev/min, 4.7 bar IMEP_n (main chamber fuel - pre chamber fuel) [2].