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Investigation of Ignition Energy with Visualization on a Spark Ignited Engine powered by CNG

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Abstract

The need for using alternative fuel sources continues to grow as industry looks towards enhancing energy security and lowering emissions levels. In order to capture the potential of these megatrends, this study focuses on the relationship between ignition energy, thermal efficiency, and combustion stability of a 0.5 L single cylinder engine powered by compressed natural gas (CNG) at steady state operation. The goal of the experiment was to increase ignition energy at fixed lambda values to look for gains in thermal efficiency. Secondly, a lambda sweep was performed with criteria of maintaining a 4% COV_{IMEP} by increasing the ignition energy until an appropriate threshold for stable combustion was found. The engine performance was measured with a combustion analysis system (CAS), to understand the effects of thermal efficiency and combustion stability (COV_{IMEP}). Emissions of the engine were measured with an FTIR. The engine was instrumented with visualization equipment to capture real-time combustion images. The results show that increasing the ignition energy will increase the thermal efficiency of combustion by roughly 2-3%. In areas of lean combustion, the ignition energy level plays a pronounced role in the COV_{IMEP} of the engine. At λ = 1.25, drastic improvement of COV_{IMEP} was realized based on increasing the energy level. Additionally, the reduction of NOx, CO, and THC emissions is possible as they also are sensitive to the amount of ignition energy.

Introduction

A major goal currently in automotive Powertrain is to increase engine efficiency for the sake of CO_2 emissions reduction. The drive for this trend is the result of increased federal emissions regulations that will raise the required fleet average fuel economy in first the 2018MY then again in 2025MY light-duty vehicle applications. Due to these aggressive fuel economy targets, new technologies have begun to emerge in engine architecture. Most OEM's have begun to introduce advanced Powertrain technology in their line-up which will meet the fuel economy regulation and still provide adequate Hp to the consumer. Some of these technologies include but are not limited to: lean-burn combustion, high-boost turbo-charger/super charger systems, VVT, high tumble valves, and EGR loops. As a result of using the previously mentioned combustion strategies and engine technologies, the combustion stability will be reduced and the required energy for the ignition system must be enhanced to meet the high energy demands.

In parallel there is another trend in transportation. This refers to reducing the dependence on crude oil by moving away from conventional gasoline and increasing the usage of alternative energy sources. One such alternative energy is natural gas, compressed in a tank for mobile use. This is known as compressed natural gas (CNG). Natural gas offers a viable near-term solution to decrease consumption of crude oil. Natural gas is the cleanest of all the fossil fuels, as shown in the Environmental Protection Agency's data comparisons seen below in Table 1. The combustion of natural gas compared to that of oil and coal releases very small amounts of sulfur dioxide and nitrogen oxides, virtually no ash or particulate matter, and lower levels of carbon dioxide, carbon monoxide.

Table 1. Fossil Fuel Emission Levels [1].

Pollutant	Natural Gas	Oil	Coal
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448	457
Sulfur Dioxide	1	1,122	2,591
Particulates	7	84	2,744
Mercury	0.000	0.007	0.016

Units: Pounds per Billion Btu of Energy Input

Natural gas can be used in many ways to help reduce the emissions of pollutants into the atmosphere [1]. It should also be mentioned that unburned methane emissions have high global warming potential [2]. Natural gas has many constituents other than methane which may contribute to emissions. These emissions can be measured using laboratory emissions equipment.

CNG is a clean and viable fuel to use as an alternative to petroleum refined from crude oil. Significant reductions in regulated tailpipe emissions can be achieved by changing from gasoline to alternative fuels. Power density can be further increased through supercharging, resulting in comparable torque output and volumetric efficiency in medium-duty gasoline engines [3]. Further reductions in emissions could be realized if a comprehensive calibration program was undertaken. These reductions are possible without the need to use catalyst formulations that differ from the standard gasoline vehicle, that is to say that TWC technology is already good enough for use on CNG vehicles when operating at stoichiometric air-fuel ratios. While this study looks mainly at lean operation, it should be noted that in these cases standard TWC may not be the only after-treatment required to meet the emissions regulation. It is possible to estimate the theoretical reduction in CO_2 that might be achieved with CNG fuel when compared with gasoline. This is done using the equations of combustion for gasoline, methane (the main component of CNG) in conjunction with the specific heating values of the fuels [4]. Therefore, the emissions from CNG are cleaner and produce less harmful bi-products which are then released into the environment when compared to current engines running on gasoline.

In terms of combustion advantages of using CNG, the octane level of CNG compared to convention pump grade fuel is increase from approximately 90 to 118. By using fuels with better antiknock properties, engine compression ratios steadily increase, thus improving power and efficiency [5]. By using a fuel with a higher octane rating, the knock margin of the engine can then be increased and a higher efficiency engine calibration strategy can be used. Also by using a fuel with higher octane, more spark advance is possible as the risk of pre-ignition is reduced [6]. The key to a reliable combustion is to establish a stable flame kernel in the ignition zone. A number of experimental and production technologies already exist to serve this function.

In this experiment a state of the art ignition system will be used on an engine converted to CNG that will run at several air/fuel ratios to understand the effect of higher energy levels will have on thermal efficiency of the engine or if more stable lean limits can be achieved.

Experiment Setup and Method

Experiment Setup

In this experiment a 2.0 L, 4 cylinder, direction injection gasoline engine was used with only one cylinder active.

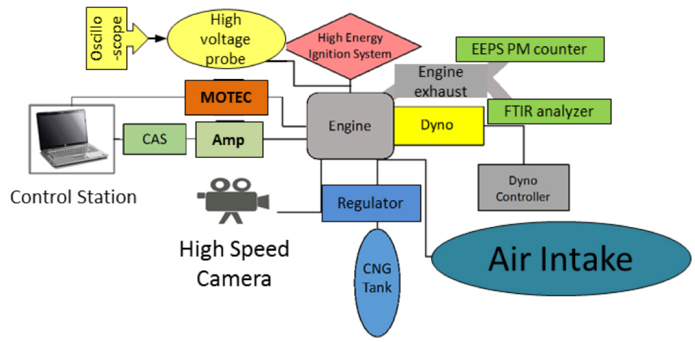


Figure 1. Schematic of engine bench test set-up.

A CNG fueling system and high energy ignition system are also assembled on the engine. A universal-joint type drive-shaft is used to connect the engine to the dynamometer. The dynamometer is a DC dynamometer which could be only used for steady-state testing.

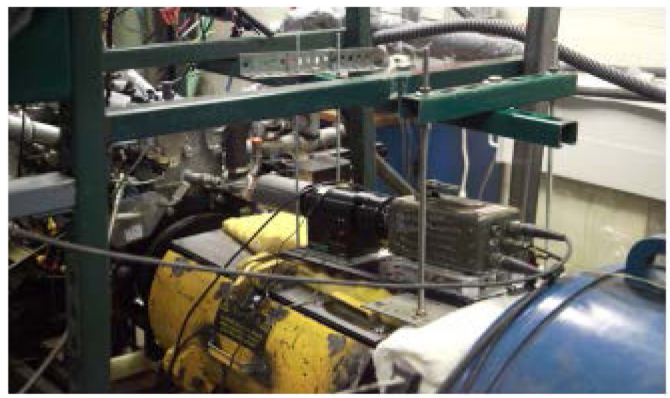


Figure 2. Picture of dyno connected to engine with camera.

The air throttle was removed and the intake system was kept steady at approximately 0.5 bar. Table 2 shows the engine specification.

Table 2. Single cylinder engine specifications.

Base engine	2.0 L I4 LHU
Configuration	Single cylinder
Displacement	500cc
Compression ratio	9.2:1
Valve configuration	DOHC
Valves per cylinder	4
Bore x stroke	86mm x 86mm
Fuel system	PFI CNG system retrofitted
Injection pressure	7.6 bar

During this experiment a modified engine head provided a direct visual path into the combustion chamber of the engine.

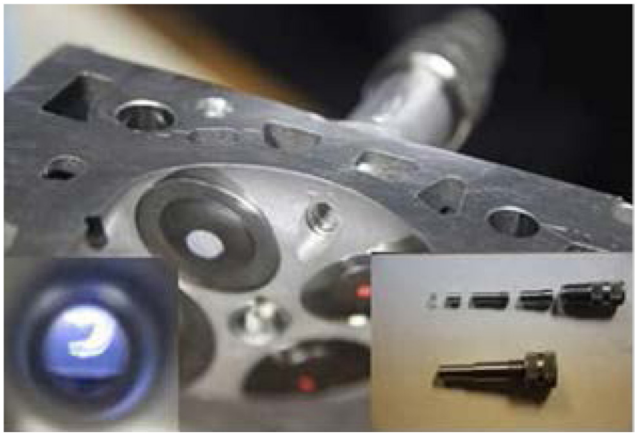


Figure 3. Combustion visualization apparatus.

As seen in Figure 3, the cylinder head had a hole machined in the side through the water jacket, and a sapphire glass window was installed providing a path to view the spark event while the engine was fully operational. In previous experiments, direct optical access to the combustion chamber has been shown to a useful research tool to obtain better understanding of combustion through direct observation. Therefore this method is again applied to this experiment [7]. The optical system used in this experiment used an intensified high speed camera with a frame rate of 1 frame per 1 CA. Therefore operating at 1200 RPM was the equivalent of 7200 frames per second. However to minimize memory of the recording, start triggered on the firing event and took approximately 180 frames of data. The images were recorded using only luminosity from the ignition and subsequent combustion.

An MKS FTIR analyzer (HS-2030) is implemented in the exhaust pipe. All sampling lines used for these benches are heated and kept at 191 °C to eliminate the influence of water condensation. The MKS analyzer is an implementation of Fourier-transform infrared (FTIR). It is capable of ppb to % sensitivity for measurement of multiple gases in many applications, e.g. catalysis and combustion process monitoring, emission monitoring, and etc. The type used in this experiment is a high-speed analyzer (5 Hz).

Experiment Method

The study focuses on the ignition energy requirements of CNG when using different air-fuel ratios. By varying the ignition energy, the effects on combustion are observed. Advanced ignition system design and operation may impact engine combustion [8, 9, 10, 11]. The different fuels as well as different energy levels were investigated on the engine previously described in Chapter 2. The main focus is on Coefficient of Variation of Indicated Mean Effective Pressure (COV_{IMEP}) values and the thermal efficiency of the system based in the Indicated Mean Effective Pressure (IMEP). The process of the test methods used is described in this section.

Table 3. Summary of testing criteria.

Test	Engine RPM	MAP	Lambda	Ignition Energy (mJ)
A	1200	0.5 bar	1.25	36
				65
				180
				240
B			1.2	36
				65
				180
				240
C			1.15	36
				65
				180
				240
D			1	36
				65
				180
				240
E			0.9	36
				65
				180
				240

The summary of the testing criteria can be seen in Table 3. There were 5 lambda values used as test points as well as 5 different variation of ignition energy. Test points were all taken at steady-state conditions representing a low speed high load condition.

In this experiment TDC refers to the firing TDC. Spark was fixed at a constant 10 °CA bTDCf. The criteria was based on results that studied of ignition energy on this engine, where A/F was fixed at λ = 1.15, and three spark timings were swept using 20 °CA bTDCf, 15deg bTDCf and 10 °CA bTDCf. The combustion stability is compared in Figure 4.

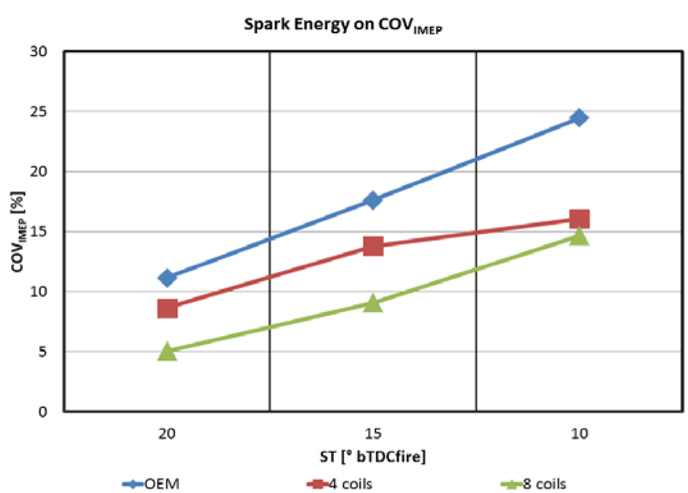


Figure 4. Spark timing comparison using COV_{IMEP}.

Based on information from Figure 4, it was determined that the area of 10 °CA bTDCf was the worst for COV_{IMEP}, so this timing was chosen to focus on for impacts of ignition energy.

Testing Procedure

All experiments are done by the following test procedure. These procedures are considered as steady state.

1. Warm up the engine with a coolant heater until the coolant temperature reaches 40 °C. Air temperature is as the room temperature, which is about 25 °C.
2. Start the engine at 1200 RPM.
3. Start CAS, camera recording, and data acquisition if the combustion is stable.

The tests are conducted according to the following parameters:

- MAP: 0.5 bar
- Injection timing: 300 °CA bTDCf
- Injection pressure: 7.6 bar (110 psi)
- Ignition timing: 10 °CA bTDCf
- Lambda: 1.25, 1.2, 1.15, 1.0, 0.9
- Spark discharge energy: 36 mJ, 65 mJ, 180 mJ, 240 mJ

Results and Discussion

CNG fuel was tested with multiple levels of ignition energy. The testing results are separated lambda value and combustion analysis. The authors utilize a specially made device to generate different spark discharge energy to study the impact on engine combustion. The main variables of the ignition process were initial energy discharge and arc duration. The test results show that increasing the energy could improve the combustion in an otherwise unstable operating condition [9]. Figure 5 shows the results of IMEP and Figure 6 shows the results of COV_{IMEP}. IMEP and COV_{IMEP} both show significant improvement when ignition energy is increased. It should be noted that even though 65 mJ and 240 mJ show little difference in IMEP, there is a noticeable improvement in COV_{IMEP}.

Spark Energy Visualization

Using direct visualization of the combustion chamber helps to understand the variation in spark luminosity based on varying the ignition energy. The visual intensity of the spark varies greatly depending on the amount of available spark energy from the coil. Seen below in Tables 4, 5, 6, 7, 8 the visualization of four different spark energies are shown over a period of 8 °CA bTDCf at 5 different lambda values. This visualization captures the initial energy, arc length, and arc duration of the ignition event. The term ‘arc length’ is defined as the physical size of the spark as it is being stretched across the spark plug electrodes, and ‘duration’ is the amount of time the spark event stays intact. These both depend on ignition energy and charge motion. The initial energy is the initial ignition event that occurs when the spark gap is first energized. The arc length is the amount of time spark travels between electrodes of the plug.

Table 4. Visualization of spark over 8° CA bTDCf at λ = 1.25.

Lambda = 1.25 at 10°CA bTDCf				
	-8deg TDC	-6deg TDC	-4deg TDC	0deg TDC
OEM coil				
65mJ (4x1 coil)				
180mJ (2x2 coil)				
240mJ (4x2 coil)				

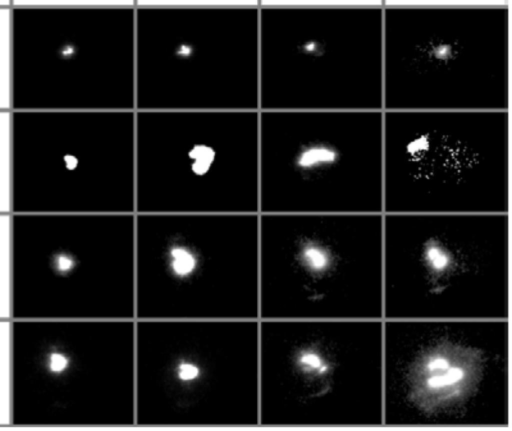


Table 5. Visualization of spark over 8° CA bTDCf at λ =1.2.

Lambda = 1.2 at 10°CA bTDCf				
	-8deg TDC	-6deg TDC	-4deg TDC	0deg TDC
OEM coil				
65mJ (4x1 coil)				
180mJ (2x2 coil)				
240mJ (4x2 coil)				

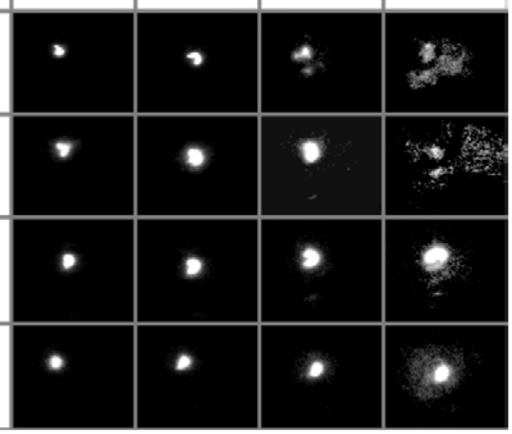


Table 6. Visualization of spark over 8° CA bTDCf at λ = 1.15.

Lambda = 1.15 at 10°CA bTDCf				
	-8deg TDC	-6deg TDC	-4deg TDC	0deg TDC
OEM coil				
65mJ (4x1 coil)				
180mJ (2x2 coil)				
240mJ (4x2 coil)				

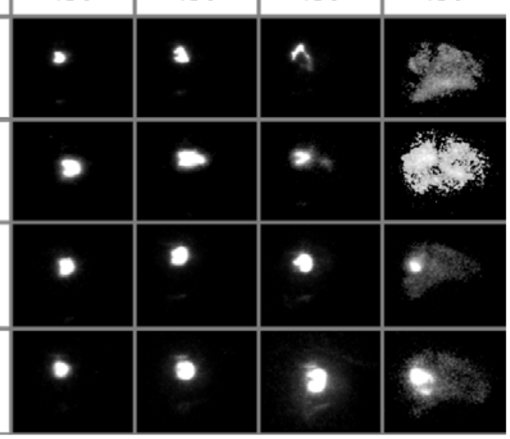


Table 7. Visualization of spark over 8° CA bTDCf at λ = 1.0.

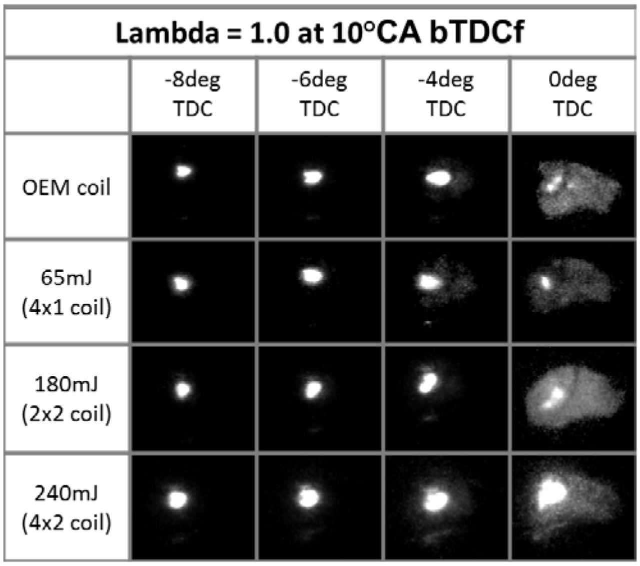
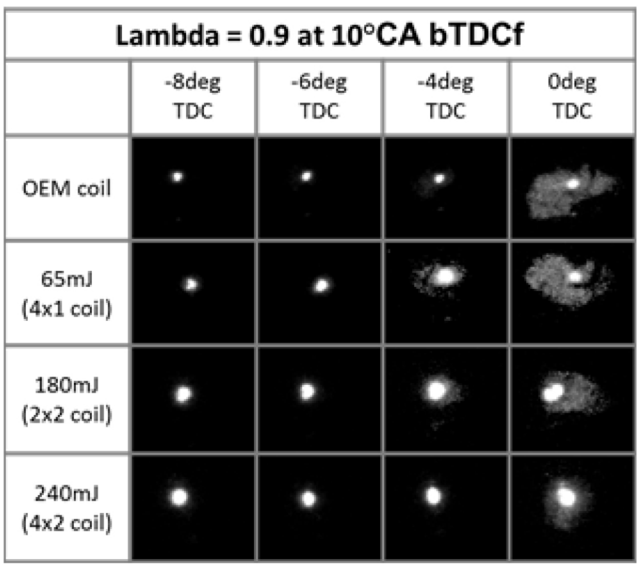


Table 8. Visualization of spark over 8° CA bTDCf at λ = 0.9.



Tables 4, 5, 6, 7, 8 show the image results of CNG combustion with varying amounts of coil energy at multiple lambda values. The images show that with a lesser amount of available coil energy, the spark appears weaker than the spark from coils with more available energy. As seen in Tables 4, 5, 6, 7, 8, the more energy available from the coil, the longer the length of the arc will grow. At the leanest testing condition of λ = 1.25, the flame kernel after 8° CA bTDCf using 240 mJ shows a noticeable larger flame kernel than the conditions lower ignition energy. This shows that spark energy have a direct correlation to the flame propagation, and can be seen in the corresponding combustion and emissions data.

Engine Data

There were several combustion calculations, such as indicated mean effective pressure (IMEP), coefficient of variation (COV_{IMEP}) of IMEP, and thermal efficiency, which will be displayed and discussed in this section. Table 9 shows a summary of the test results. It should be noted that the results exclude data from the OEM coil, and instead include data from a 36 mJ coil variant that is not included in Tables 4, 5, 6, 7, 8 or in the emissions section.

Table 9. Summary of results.

	Lambda	IMEP	COVIMEP
36mJ	λ = 1.25	6.03	13.22
	λ = 1.20	7.68	5.19
	λ = 1.15	8.76	3.42
	λ = 1.00	10.53	1.26
	λ = 0.90	10.34	1.74
65mJ	λ = 1.25	6.57	10.46
	λ = 1.20	8.32	3.91
	λ = 1.15	9.14	2.98
	λ = 1.00	10.79	1.34
	λ = 0.90	10.54	1.94
180mJ	λ = 1.25	7.29	7.18
	λ = 1.20	8.18	5.02
	λ = 1.15	9.23	2.52
	λ = 1.00	10.83	1.39
	λ = 0.90	10.48	2.64
240mJ	λ = 1.25	7.09	7.72
	λ = 1.20	8.46	3.76
	λ = 1.15	8.86	2.97
	λ = 1.00	10.87	1.39
	λ = 0.90	10.54	2.21

Indicated Mean Effective Pressure (IMEP)

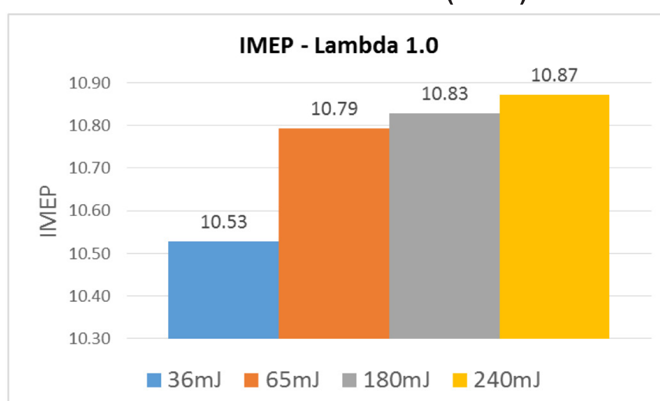


Figure 5. IMEP results at λ = 1.0.

The IMEP graph seen in Figure 5 shows that at λ = 1.0 there is a 3.2% increase in IMEP is observed between 36 mJ and 240 mJ of ignition energy. When comparing these results to Table 4, there is clearly a longer arc duration seen by the high luminosity across the gap region of the spark plug. With these results we can validate higher IMEP as a function of higher energy.

Coefficient of Variation (COV_{IMEP})

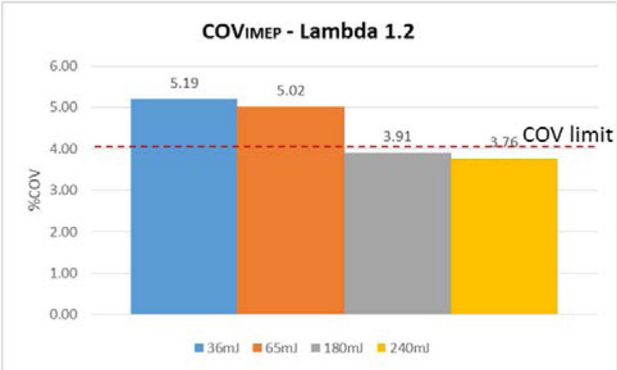


Figure 6. COV_{IMEP} results at λ = 1.2.

The COV_{IMEP} results in Figure 6 show that when operating at a λ = 1.20, ignition energy plays a large role in engine performance. The target of 4% COV_{IMEP} is used as an acceptable limit for operation. This criteria was chosen as an acceptable level of combustion stability for the engine. COV_{IMEP} values higher than 4% could result in rough engine operation or possibly engine misfire, and thus could not be used in vehicle calibration. A noticeable effect of COV_{IMEP} is observed by varying ignition energy between 36 mJ and 240 mJ. Here by applying a higher amount of ignition energy, we can get the combustion COV_{IMEP} under the 4% limit.

Thermal Efficiency - Otto Cycle

For this experiment the LHV of CNG was calculated as 3996.3 kJ/m^3. By using the LVH of the fuel and the flow rate determined by the injection pressure and the injector pulse width, the energy into the system could be calculated. The breakdown of the fuel constituents in CNG used for this experiment is shown in Table 5:

Table 10. List of CNG constituents by percent.

Gas	MOL%	LHV (kJ/m^3)
Methane	0.95661	34073.3
Ethane	0.01736	61067.4
Propane	0.00225	88378.2
I-Butane	0.00038	115689
N-Butane	0.00042	111404.25
I-Pentane	0.00015	138454.25
N-Pentane	0.0001	145310
Hexanes	0.0001	164386.5

This number was divided into the IMEP multiplied by the displacement of the cylinder to provide a thermal efficiency value.

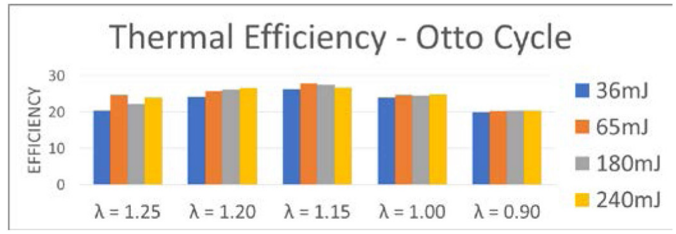


Figure 7. Thermal efficiency results.

As seen above in Figure 7, lean condition is more susceptible to ignition energy. By using higher amounts of ignition energy, more work is extracted from the fuel. Through fluctuation of ignition energy, an increase of 3% thermal efficiency observed. The highest thermal efficiency was achieved λ = 1.15. This is probably because spark timing of 10 °CA bTDCf is closer to MBT at that operating condition. It is also possible that the decrease in thermal efficiencies are observed as the engine goes leaner than λ = 1.15 because the combustion phasing is late and combustion duration is longer.

Emissions Data

Using an MKS FTIR analyzer (HS-2030), the following emissions information was measured. In order to verify consistent results, the engine oil and coolant temperatures were allowed to stabilize for 2 minutes before sampling combustion gases. The highest CO_2 is observed at λ = 1.00. This verifies that the most complete combustion occurs at stoichiometric condition. The highest CO is at the rich condition, and the highest NOx is also at λ = 1.00. The relationship between CO_2/CO/CH_4 shows the optimal completeness of combustion [4]. This relationship is seen in the figures by looking at the data from 65 mJ. This trend shows high CO_2 values and inversely low levels of CH_4 and CO. It should also be noted that with conventional TWC technology, the emissions of this engine when using CNG will be lower than the same conditions when using gasoline [3].

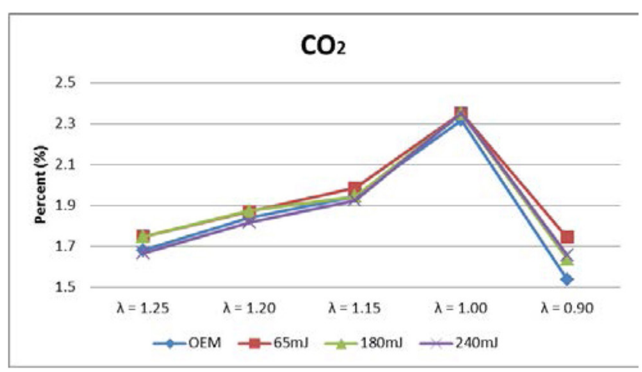


Figure 8. FTIR results of CO_2.

In Figure 8, the CO_2 emissions results are measured using an FTIR machine. Best performance of CO_2 emissions are at stoichiometric conditions. The biggest variation of CO_2 is seen when operating in a rich condition λ = 0.90. This could be the result of higher unburnt methane in the exhaust. The difference is approximately 20% of the total CO_2% value. At lean operation, effect on CO_2 is minimal.

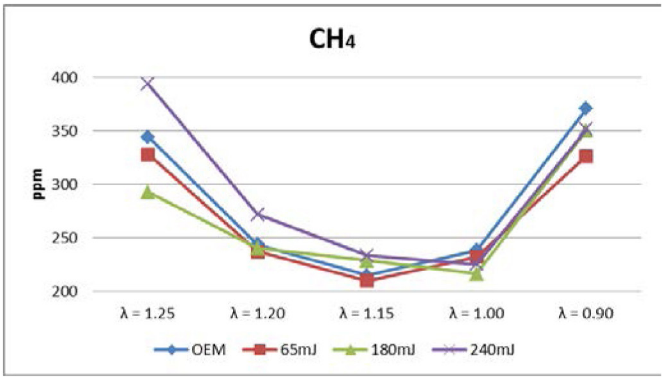


Figure 9. FTIR results of CH_4.

In Figure 9, the CH_4 results are measured using FTIR emissions results. The biggest effect observed is when the engine is operating in a lean condition λ = 1.25. There is approximately a 55% difference in total CH_4 emissions. Based on these results, at this condition the coil configuration with the longer arc duration has a greater effect than the higher initial energy.

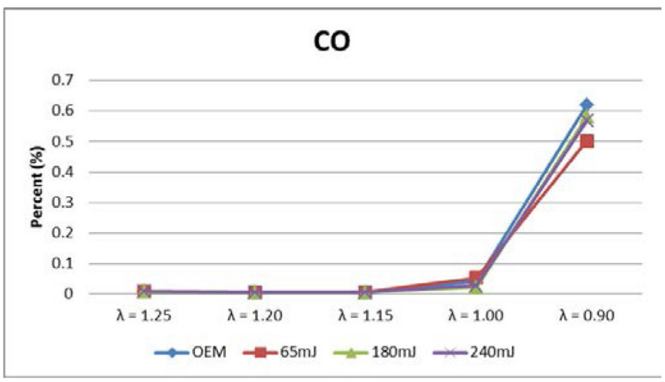


Figure 10. FTIR results of CO.

In Figure 10, effects of CO emissions are illustrated. Rich condition λ = 0.90 has the largest effect of CO emissions. About a 20% difference emissions is observed depending on the coil configuration. Based on these results observed at this condition, the optimal ignition strategy for minimal CO emissions is a high initial energy discharge with no benefit observed for an increase of arc duration.

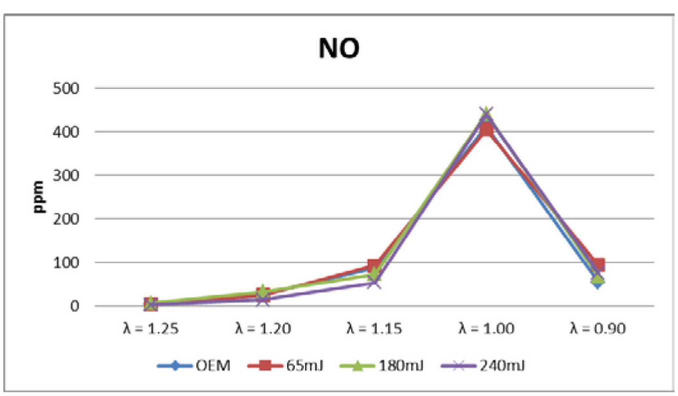


Figure 11. FTIR results of NO.

In Figure 11, the NO results are shown. Ignition energy has virtually no effect on the NOx emissions of the engine. It should be noted that NO_2 was relatively low comparing to NO, therefore NO is considered as the primary NOx emission.

Summary/Conclusions

The present study primarily focuses on the effects of ignition energy on the combustion performance on an engine using CNG. CNG fuel was tested with multiple levels of ignition energy. The testing results are separated by lambda value and combustion analysis. The results indicate the following conclusions:

- Higher spark energy could improve the combustion process and reduce cycle-to-cycle variation.
- During stoichiometric operation, more complete combustion occurs.
- Indicated thermal efficiency is greater in lean operation meaning more useful work is extracted from the fuel.
- Ignition energy has a minimal effect on emissions at these tested conditions. However long arc duration produced the best results for THC and high initial energy produced the best results for CO.

The COV_{IMEP} criteria of 4% was achieved at λ =1.20, thus proving that the amount of ignition energy has a direct impact on the combustion stability of the engine. This is due to creating a higher initial energy, bigger arc length, and longer arc duration. Direct visualization of the combustion chamber can help to understand the differences in spark energy. The visual intensity of the spark varies greatly depending on the amount of available spark energy from the coil. The images show that with a lesser amount of available coil energy, the spark is relatively weaker than spark from coils with more available energy. The more energy available from the coil, the longer the length of the arc will grow and have higher probability of ignition. Thus spark energy has a direct correlation to the flame propagation, and can be seen in the corresponding combustion and emissions data.

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Definitions/Abbreviations

bTDCf - Before Top Dead Center Firing

CA - Crank Angle

CAS - Combustion Analysis Software

CH_4 - Methane

CNG - Compressed Natural Gas

CO_2 - Carbon Dioxide

CO - Carbon Monoxide

COV_{IMEP} - Coefficient of Variation of IMEP

DOHC - Dual Over Head Cam

EGR - Exhaust Gas Recirculation

FTIR - Fourier Transform Infrared

Hp - Horsepower

IMEP - Indicated Mean Effective Pressure

LHV - Lower Heating Value

MAP - Manifold Air Pressure

MBT - Maximum Best Torque

mJ - Millijoule

NOx - Nitrogen Oxide

OEM - Original Equipment Manufacturer

RPM - Rotations per Minute

TDC - Top Dead Center

TWC - Three Way Catalyst

VVT - Variable Valve Timing

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE’s peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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