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ON-ENGINE DEMONSTRATION OF MICRO-PILOT IGNITION SYSTEM FOR A COOPER-BESSEMER GMV-4TF

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ABSTRACT

This investigation assesses the benefits of retrofitting a diesel micro-pilot ignition system on a Cooper-Bessemer GMV-4TF two-stroke cycle natural gas engine with a 14" (36 cm) bore and a 14" (36 cm) stroke. The pilot fuel injectors are mounted through an adaptor in one of the spark plug holes in a set of dual-spark plug heads. A high pressure, common-rail, diesel fuel delivery system is employed and customizable power electronics control the current signal to the pilot injectors. Pilot fuel is supplied by a variable displacement, high-pressure pump that is driven with an electric motor. Software is developed that interfaces with the pump and controls and monitors the fuel rail pressure.

Micro-pilot quantities from 11.5 to 20 mm^3 (.0007 to .0012 in^3) are explored at rail pressures from 200 to 1400 bar (2,900 to 20,300 psig). Three independent variables, pilot ignition timing, pilot fuel quantity, and pilot fuel rail pressure, are manipulated. An optimization sequence is performed to minimize total fuel consumption.

KEYWORDS: Micro-pilot, Ignition, Common Rail Injection, Dual Fuel

INTRODUCTION

The U. S. pipeline industry employs approximately 8,000 reciprocating engines to compress and pump natural gas across the country. These engines represent in excess of 7 gigawatts or 9.4 million horsepower. Low compression ratio, slow speed, large bore, low brake-mean-effective-pressure (bmep), 2-stroke engines are by far the most used in the industry. Almost all of them are over 20 years old and most are nearing 40 and 50. Growing environmental concerns that brought about the Clean Air Act Amendment of 1990 have forced these elderly engines to reduce their emissions of hazardous air pollutants and NOx below their original design point value. The cost of replacing a significant part of the 8,000 natural gas reciprocating engines in the pipeline to meet new emissions requirements is prohibitive. Therefore, a host of retrofit aftermarket technologies are being developed and implemented to help old engines meet new standards.

Dual fuel ignition represents one of the technologies that a number of engine manufactures have conducted research on and even brought to market on some of their newest engines. In a natural gas dual fuel engine, the gas is the primary fuel. It is either inducted along with the intake air or directly injected into the cylinder. The gas/air mixture does not auto-ignite because the natural gas has a very high self-ignition temperature. A small amount of "pilot" fuel is injected to initiate combustion. Many pilot fuels can be used. The only condition is that the pilot self ignites at the temperature and pressure of the combustion chamber at the injection time. Diesel is the most popular choice due to its availability and relatively low cost. Some of the most advanced natural gas engines made in the last five years use diesel pilot technology in which the pilot fuel represents less than 1% of the total combustion energy. These new ignition systems, with pilot quantities below 1%, are referred to as micro-pilot ignition systems. A smaller quantity of required pilot fuel obviously decreases fuel costs but also minimizes any NO_x emissions formed by the pilot fuel.

Of the many retrofit technologies being offered to improve pipeline engines at this time, none have attempted to implement micro-pilot ignition on old engines. Research shows that a well functioning micro-pilot aftermarket system would have a lot to offer by reducing certain emissions and by eliminating the spark plug and spark plug maintenance costs.

Using pilot injection will provide a voluminous and very energetic source of ignition with respect to spark. This is well matched with lean mixtures of methane that are characteristic of many pipeline engines, particularly at partial load. Also, the slow flame propagation of methane becomes less limiting with distributed ignition points. Because of these advantages, it has been shown that pilot-ignited natural gas combustion can match diesel efficiencies and produce lower NO_x [1] and particulate emissions [2].

EXPERIMENTAL EQUIPMENT AND CONDITIONS

The Large Bore Engine Test-bed (LBET) is housed in the Engines and Energy Conversion Laboratory (EECL) at Colorado State University. At the core of the test-bed is a highly instrumented Cooper-Bessemer GMV-4TF engine. A photograph of the engine is shown in Figure 1. The GMV-4TF is a 4 cylinder two-stroke cycle, 14” (36 cm) bore, 14” (36 cm) stroke, natural gas fired engine. The GMV-4TF has a sea level brake power rating of 440 bhp (330 kW) at 300 rpm. The GMV-4TF uses Mechanical Gas Admission Valves (MGAV), which deliver fuel to each cylinder individually at an injection pressure of about 22 psig (152 kPag). The engine is nominally operated with spark ignition.

The LBET includes a combustion analysis system that uses cylinder pressure profiles to calculate peak pressure, location of peak pressure, misfire frequency, and combustion stability parameters. The test-bed has a computer controlled water brake dynamometer for precise load control. A turbocharger simulation package controls intake and exhaust manifold pressures, allowing the simulation of a wide range of engine “breathing” configurations. The turbocharger simulation package is composed of two main components, a screw type compressor driven by an electric motor to pressurize the intake air and a motorized, computer controlled backpressure valve. The facility also has the ability to control jacket water temperature, air manifold temperature, and air manifold relative humidity. The test-bed utilizes a standard five-gas analyzer rack for measuring THC, NO, O_2, CO_2, and CO, and a Fourier Transform Infrared (FTIR) spectrometer for examination of a wide range of species including criteria pollutants and formaldehyde.

Variations in engine operating parameters and changes to engine hardware configuration are performed relative to the nominal operating conditions and hardware configuration. The nominal operating conditions and hardware configuration are summarized in Table 1.

The injection of the micro-pilot fuel is performed by a combination of Delphi, Woodward, and custom hardware and software (Figure 2). A Delphi diesel common rail injection pump and injectors deliver the pilot fuel. The system is capable of creating 1,000 to 24,000 psig of fuel pressure to inject through a 24 volt electronically controlled injector. This Delphi system is used to allow a large range in injection pressures to be studied. Custom software and hardware interfaces with the Delphi equipment to vary the fuel rail pressure and monitor the fuel temperature. The Delphi injectors are driven with a modified Woodward In-Pulse engine control unit. The In-Pulse creates the specific current waveform needed to actuate each injector and times each injection event with the engine’s speed and crank angle. The timing and duration of the pilot event for each cylinder can be independently tuned using Woodward software.

Figure 1: The Cooper Bessemer GMV-4TF Large Bore Natural Gas Engine.

ENGINE PARAMETER	NOMINAL VALUE OR SPECIFICAION
Brake Power	440 hp (330 kW)
Dynamometer Torque	7730 ft-lb (10.5 kN-m)
Engine Speed	300 rpm (5 Hz)
Ignition Timing	10.1º BTDC
Intake Manifold Pressure	13.5”Hg (25 kPag)
Engine Pressure Drop	2.5”Hg (8.5 kPa)
Overall A/F Ratio	43
Trapped A/F Ratio	22
Compression Ratio	9.58 : 1
Average Peak Pressure	505 psia (3.48 MPa)
Intake Manifold Temperature	110ºF (317 K)
Intake Humidity Ratio	0.034
Jacket Water Temperature	160ºF (340 K)
Ignition	Single Strike, Spark
Fuel Delivery	Direct Injection, Mechanical, 22 psig (152 kPag)

Table 1: Nominal operating conditions for the GMV-4TF.

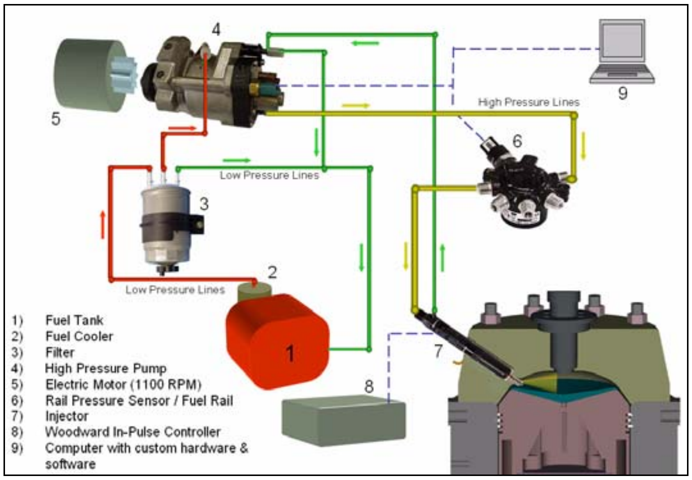

Figure 2: Micro Pilot Delivery System

INVESTIGATED MICRO-PILOT VARIABLES

Ignition of a premixed air/fuel mixture using small volume pilot ignition ("micro-pilot") depends on many variables. Four of these variables are due to the engine characteristics:

- Compression ratio in the cylinder
- Pressure in the cylinder
- Temperature in the cylinder
- Air/Fuel ratio

Five others are inherent to the pilot injection system:

- Cetane number of the pilot fuel
- Injector nozzle design
- Pilot injection timing
- Pilot fuel quantity
- Pilot delivery pressure

This experiment holds constant the compression ratio, in cylinder temperature, the configuration of open chamber combustion, the pilot fuel cetane rating and the injector nozzle design. By holding these variables constant, trends created by changes in the control characteristics of the pilot injection system are easily identified.

It is important to note that the design of the pilot injector nozzle, and therefore the spray pattern, are not designed for this engine. They are designed for a European marketed Ford Focus diesel engine and were selected for the their ability to deliver the correct range of pilot fuel quantities and pressure s for the GMV-4TF. The spray pattern created by the current nozzle impinges both on the top of the piston and the surface of the head. To completely optimize this pilot system, we will test other nozzle designs in the future.

Pilot Injection Timing

The effect of pilot injection timing on engine performance is very similar to spark timing. The combustion event will commence sooner when the pilot fuel is injected earlier and visa versa. However, unlike spark, the pilot ignition delay will vary with the timing of the injection.

The time measured from the beginning of pilot fuel injection to the point at which the fuel ignites is referred to as ignition delay. This delay will vary with the type of fuel as well as the temperature, pressure, and turbulence of the environment,
which is why it will also change with the timing of the pilot fuel's injection.

It is desirable to have liquid droplets present when ignition temperature is reached, whereby ignition occurs at the stoichiometric zone surrounding the droplet. If the pilot fuel injection is advanced too far, the pressure and temperature will not be sufficient to initiate combustion. In this case, fuel will continue to vaporize and mix with surrounding gases before cylinder conditions are favorable for ignition. The ideal liquid droplets have vaporized and the spray is in effect too lean and the engine will miss. This creates a limit for advancing the average peak pressures of the engine that is not found with spark ignition. Given that the pilot fuel ignites, its ignition delay will decrease as it is injected closer to top center because the reactant temperature increases as the cylinder gases are compressed by the piston.

Modeling of the GMV predicts a pressure of 250psi and a temperature of 764 K at 15 BTDC. Two previous studies of diesel ignition delay have been reviewed. A quiescent chamber based study by Wolfer predicts 6.64 ms and an engine based study by Hardenberg and Hase, which considers piston speed, predicts 5.07 ms at these conditions.

In addition to ignition delay, there is a length of time from the injection signal to when the fuel begins exiting the nozzle. On average, this delay is about 300 usec for the Delphi injectors used. If both of these the injection and ignition delays are considered, there is a total of 6.155 ms after the injector signal before ignition is predicted to begin. At 300 rpm, this is 11.08 deg.

Pilot Fuel Quantity

The quantity of pilot fuel delivered for each combustion event is typically measured either as a liquid volume or as a percentage of the total fuel energy available for the entire combustion. Figure 3 shows how these relate along with the output power of a single cylinder. The plot shows that 8 μL of pilot fuel will supply a 110 HP cylinder with 0.5% of its fuel energy. 0.5% would be comparable to a newly designed engine with a state of the art micro-pilot ignition system. Therefore, this was the target fuel quantity.

The quantity of pilot fuel largely determines the penetration distance of the spray. Many experiments of spray penetration in diesel engines have been conducted. Largely accepted is the model developed by Dent [3], based on a gas jet mixing model for the spray. This model shows the influence spray quantity has on penetration depth, plotted in Figure 4.

It is interesting to note that Figure 4 shows that for a given injector hole geometry the injection pressure has little to no effect on the final penetration distance. This distance is strictly a function of the quantity injected.

<u>Pilot Delivery Pressure</u>

The pilot delivery pressure largely affects the droplet size. A higher rail pressure will decrease the mean droplet size. Larger droplets take longer to evaporate, allowing more time for ignition to occur. However, for the same injected quantity, smaller droplets provide more potential ignition sites. Thus, there is a trade-off between droplet diameter and the number of ignition sites. For a given set of cylinder conditions and nozzle design there will be an optimum injection pressure. The injection pressure also directly affects the speed with which the plume will reach its final penetration depth.

TESTING PROCEDURE

Testing was performed with the un-optimized nozzle to demonstrate micro-pilot feasibility for this application. Many variables could have been used to track the optimization of the pilot system including different key emissions, engine performance characteristics, and fuel consumption rates. After careful consideration, it was determined that by minimizing fuel consumption we would likely improve other important variables. In this test, fuel consumption was minimized both for natural gas and the pilot fuel during steady state operation.

A variable titled Total Modified Fuel Consumption (TMFC) was created to track the use of both fuels. TMFC represents the combined fuel consumption of pilot and natural gas, on an energy basis, with a penalty of 20 on the pilot fuel. The penalty on the use of pilot fuel is associated with the additional cost of the diesel fuel as well as its delivery, storage, and handling. At today's current prices, natural gas costs about $4.5 per one million BTU of fuel energy. Diesel fuel is about $9 per one million BTU of fuel energy. To fairly add these two fuels together on purely an energy basis, a penalty of 2 must be applied to the use of diesel fuel based only on the cost of the fuel. In addition to the higher cost of diesel, the delivery, storage, and handling of the product must be considered as well. After discussion with individuals involved with the gas industry, it was determined that a total diesel pilot penalty of 20 would be appropriate.

Optimizing the engine with three independent variables traditionally would require a very large map of data over all of the variables' ranges and combinations. To minimize the testing time, a Design of Experiments statistical technique was used. The test map is unique because it is open ended. A base matrix of data was taken and used to develop an empirical model. The matrix (Table 2) began with a center point and adjusted each of the three independent variables (Pressure, Timing, and Quantity) in a positive and negative step to acquire data at every possible combination of high and low for each variable, effectively creating a "cube" of data around the center point. The cube required the eight corners of data as well as three identical center points, to test for repeatability, resulting in eleven data points.

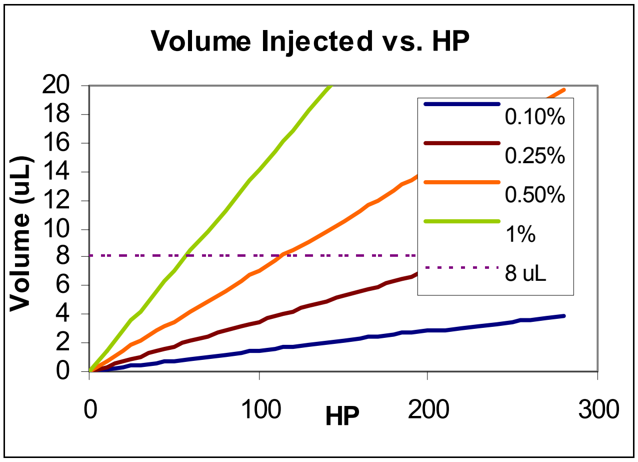

Figure 3: Volume as a function of power produced

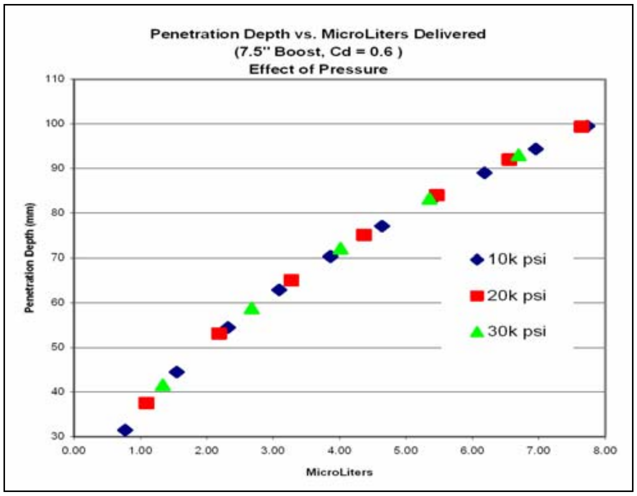

Figure 4: Penetration Depth vs. Quantity Delivered

Eleven data points was in excess of what we felt was possible to take in one test day so the cube was broken up into two blocks so that it could be tested over a period of two days. These two blocks included the eight corners of the cube and four center points, one for the beginning and one for the end of each day. The empirical model developed from the center point cube was used to create a linear vector that optimized fuel consumption by specifying a series of set points for the three independent pilot variables. This search vector was followed until a local optimum point was found. At this local optimum the experiment was repeated using the local optimum as a new center point and then determining and following a new search vector. This cycle was repeated until a true optimum was found.

All experimental points were taken with the engine at a rated load and 13.5" inHg boost. No transient studies were performed. Before any micro-pilot data was taken, a baseline was run with single strike single plug spark ignition. The spark ignition system consisted of Altronic controls and Altronic Black coils rated at 12000 volts.

Table 2: Initial Center Point “Cube” Matrix

Block	Run Order	Center Point	Rail Press (psi)	Pilot Qty (µL)	Timing (BTDC)
1	1	X	10000	14.5	14
	2		12000	13	13
	3		8000	16	13
	4		8000	13	15
	5		12000	16	15
	6	X	10000	14.5	14
2	7	X	10000	14.5	14
	8		8000	13	15
	9		12000	16	15
	10		8000	16	13
	11		12000	13	13
	12	X	10000	14.5	14

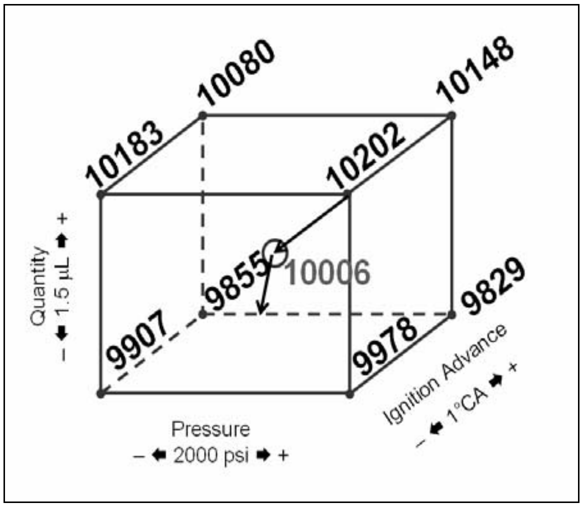

Figure 5: TMFC (BTU/hp-hr) values for initial center point matrix. Arrows show trend for lower TMFC.

Table 3: Optimization Vector Set Points

Run Order	Rail Press (psi)	Pilot Qty (µL)	Pilot % Total Energy	Timing (BTDC)
1	10000	14.50	0.90	14.00
2	8944	14.19	0.89	14.22
3	7888	13.88	0.87	14.45
4	6832	13.57	0.85	14.67
5	5776	13.25	0.83	14.89
6	4720	12.95	0.81	15.12
7	3664	12.64	0.79	15.34
8	3000	12.33	0.77	15.56
9	3000	11.50	0.72	15.56

RESULTS

The resulting Total Modified Fuel Consumption (TMFC) for the test points in Table 2 are shown in Figure 5. This cube shows that the system favored lower pilot quantities, lower pilot injection pressure, and more advanced timing.

The resulting empirical model produced an optimizing vector, which specified the direction and step size that pilot pressure, quantity, and timing should be moved to decrease TMFC. This linear vector predicted ever-decreasing values of TMFC so the actual measured value had to be tracked to find the real minimum. These new values were tested and TMFC was tracked at each point to observe when the value reached a minimum. The values used for the optimization vector are shown in Table 3 and TMFC values are plotted in Figure 6.

Point 7 of the optimizing vector proved to be the local minimum determined by following the specified pilot settings. The 9th point was a “best guess” setting based on experimenter observation.

During the each test point for minimizing TMFC, data was recorded on all major emissions constituents as well as engine performance and combustion behavior. While minimizing the TMFC, the use of gas was following a similar path as shown in Figure 7. The optimum point for TMFC however, was found to be different than that for minimum natural gas usage. As the amount of pilot fuel was reduced, natural gas consumption first trended down with TMFC, but reached a minimum at point 7. The set points for the 9th data point did not follow the model. They were a best guess based on observations made during the other test points. For this point, pilot quantity was reduced farther while holding the other timing and rail pressure constant, which resulted in lowering TMFC but raising natural gas consumption.

Other significant measurements made during this testing are shown in Figures 8 - 12. Each measurement is labeled with an abbreviation that indicates the high or low setting used for the pilot injection. For instance, “QH-TL-PH” would represent a data point taken with a high setting for pilot quantity, low setting for timing, and a high setting for pressure.

Brake specific oxides of nitrogen (bsNO$_X$) emissions, along with Total Hydrocarbon (bsTHC) emissions were reduced across the board but did not seem to trend with changes in the micro-pilot settings.

In addition to reducing the coefficient of variance of engine indicated mean effective pressure (COV of IMEP), the pilot ignition eliminated all misfires. The spark test point had an engine average of 0.925% misfire. The entirety of the pilot ignited data contained no misfire.

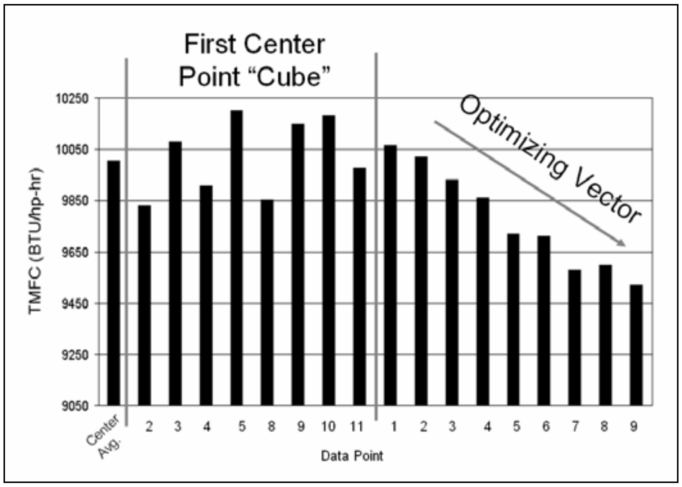

Figure 6: TMFC Values for Center Point and Optimizing Vector

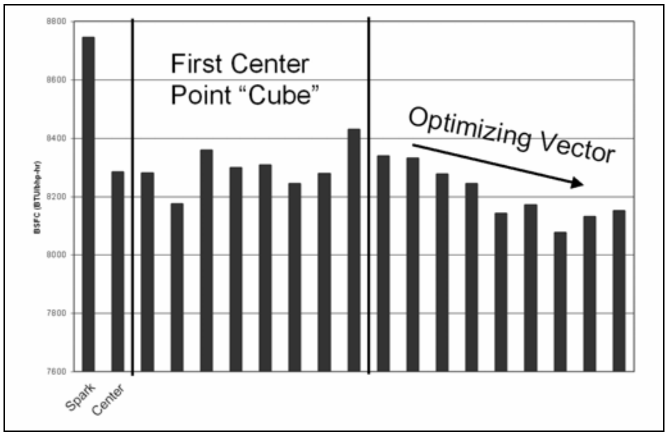

Figure 7: Natural Gas Consumption for Spark, Center Point, and Optimizing Vector

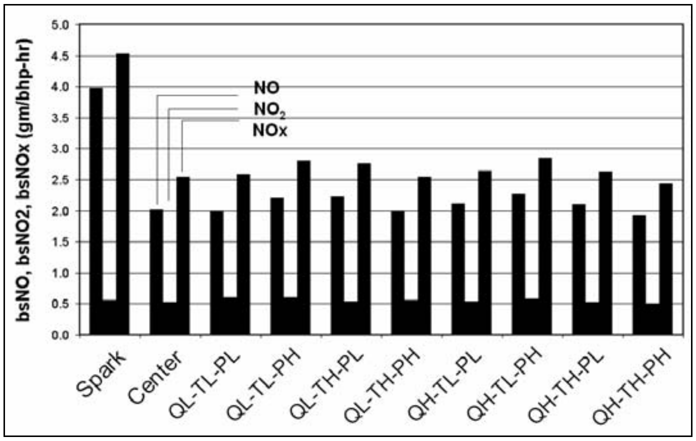

Figure 8: Brake Specific NO$_x$ formation

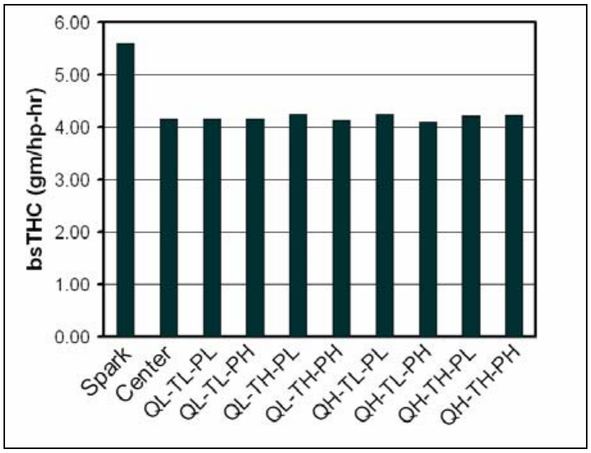

Figure 9: Brake Specific Total Hydrocarbon Formation

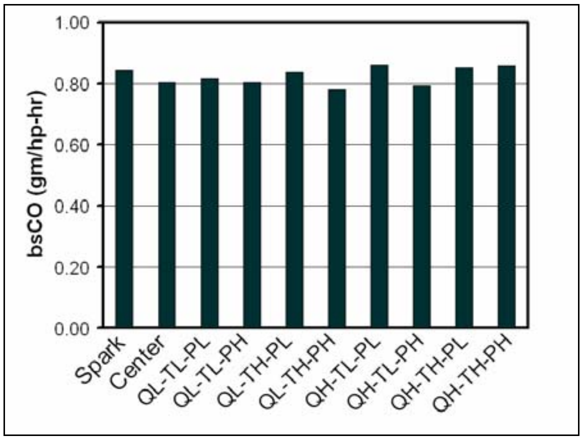

Figure 10: Brake Specific Carbon-monoxide Formation

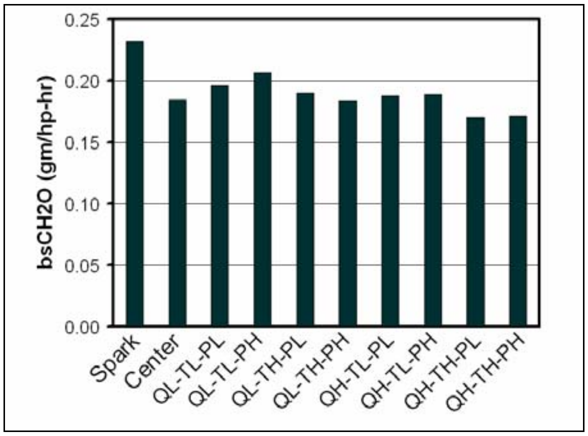

Figure 11: Brake Specific Formaldehyde Formation

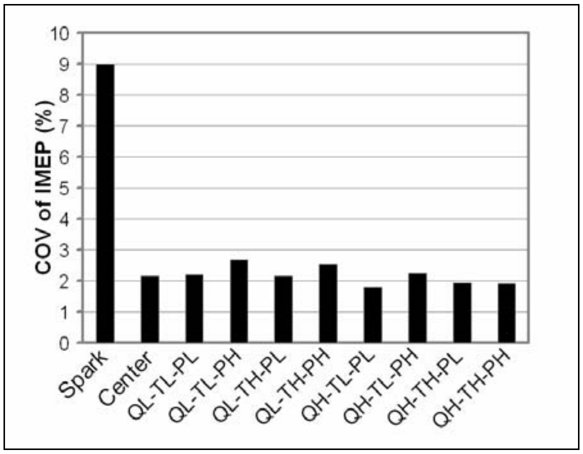

Figure 12: Indicated Mean Effective Pressure Coefficient of Variance

CONCLUSIONS

The results were very promising and the potential for an effective retrofit micro-pilot injection system for large-bore, 2-stoke cycle natural gas engines is high. The percent of fuel energy was lowered to 0.72% while still improving combustion stability and lowering key emissions with respect to spark ignition and further optimization remains to be done.

In future studies we anticipate the quantity of pilot fuel used to be reduced below 11.5 μL (0.72% total energy) in future tests. As noted above, the nozzle design tested is non-optimal for this application. It was selected for its availability and mass flow range. Post-test inspections show that it impinges both on the head and the piston. Custom nozzles are being designed for the next phase of experimental investigation. In view of this, more study needs to be carried out to determine the full potential of retrofitting large bore, 2-stroke natural gas engines with micro-pilot injection.

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