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INVESTIGATION OF MICRO-PILOT FUEL IGNITION SYSTEM FOR LARGE BORE NATURAL GAS ENGINES

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ABSTRACT

This investigation assesses the feasibility of a retrofit 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 installed in a liquid cooled adapter mounted in a spark plug hole. The engine is installed with a set of dual-spark plug heads, with the other spark plug used to start the engine. A high pressure, common-rail, diesel fuel delivery system is employed and customizable power electronics control the current signal to the pilot injectors.

Three independent micropilot variables are optimized using a Design of Experiments statistical technique to minimize a testing variable consisting of a fuel consumption and brake specific NO_x components. Micropilot variables investigated consist of pilot ignition timing, pilot fuel quantity, and pilot fuel rail pressure. Additionally, the micropilot ignition system is evaluated at two compression ratios.

INTRODUCTION

The U.S Pipeline industry operates approximately 8000 reciprocating engines to compress and transport natural gas throughout the United States. The majority of these reciprocating engines are comprised of two-stroke, slow speed, large bore, low compression ratio, low-brake-mean-effective-pressure (BMEP) engines. Increased environmental regulations created by the Clean Air Act of 1990 have forced these engines to reduce their emissions of hazardous air pollutants (HAPs) and oxides of nitrogen (NO_x) below their original design values. The cost of replacing these engines is highly prohibitive creating a need for retrofit technologies to reduce emissions within the current standards.

One of the current retrofit technologies being investigated is a pilot fuel ignition system. Pilot fuel ignition systems have been investigated by a number of engine manufactures with a high degree of success. Pilot fuel ignition systems implemented on large bore reciprocating engines employ natural gas as the primary fuel. Natural gas is either inducted into the cylinder through an intake manifold or directly injected into the cylinder. In order to initiate combustion, a small amount of pilot fuel is injected into the cylinder self igniting at compression temperatures. A variety of fuels may be used to initiate the combustion event. The primary condition for selection of a pilot fuel is that the fuel will self ignite at the pressures and temperatures present in the combustion chamber at the desired time of ignition. Diesel fuel is an inherently attractive pilot fuel due to its availability and relatively low cost. Advanced diesel pilot fuel engines have been developed that inject extremely small quantities of diesel in which the pilot fuel represents less than 1% of the total combustion energy. Pilot fuel injection systems in which the pilot fuel contributes less than 1% of the total combustion energy are referred to as micro-pilot ignition systems.

To date micro-pilot ignition systems have not played an important role in retrofitting large bore natural gas compressor engines. Research has shown that a well functioning micro-pilot ignition system can increase combustion stability, reduce certain emissions, and decrease the time and cost associated with spark plug maintenance. Use of a micro-pilot ignition system will provide a highly energetic source of ignition distributed in multiple locations within the combustion cylinder. These multiple ignition points help remedy the slow flame propagation of methane, while also enhancing the ability to ignite leaner mixtures. Due to these reasons, pilot ignition represents a viable option as a retrofit technology for the ageing large bore natural gas engines.

EXPERIMENTAL EQUIPMENT

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. 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. 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 interface 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.

EXPERIEMENTAL CONDITIONS

Ignition of a pre-mixed air/fuel mixture depends on a large amount of engine and pilot fuel system variables. Engine variables affecting the performance of the ignition system are as follows:

- Compression Ratio
- Pressure in cylinder
- Temperature in cylinder
- Air/Fuel Ratio

Additionally, there are several variables inherent to the pilot fuel system, which affect the performance of the ignition system. These pilot fuel variables are as follows:

Table 1: GMV-4TF Nominal Operating Conditions

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	8.27: 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)

- Pilot fuel injection timing
- Pilot fuel injection quantity
- Pilot fuel injection pressure
- Pilot fuel cetane number
- Fuel Injector Nozzle Design

In this experiment the pilot fuel system was optimized at two separate compression ratios. Initially, the micropilot system was optimized at the GMV-4TF stock compression ratio (8.67/8.07:1) over a variety of boost levels. The two compression ratios given are for the odd and even banks of the engine, respectively, which have different compression ratios. Following completion of stock compression ratio testing, a custom piston shim was created to increase the compression ratio to 9.48/8.75:1. Figure 1 display a solid model of the custom fabricated piston shim designed to bolt between the piston and connection rod. In addition to the custom piston shim, material was machined from the piston crown to maintain the identical

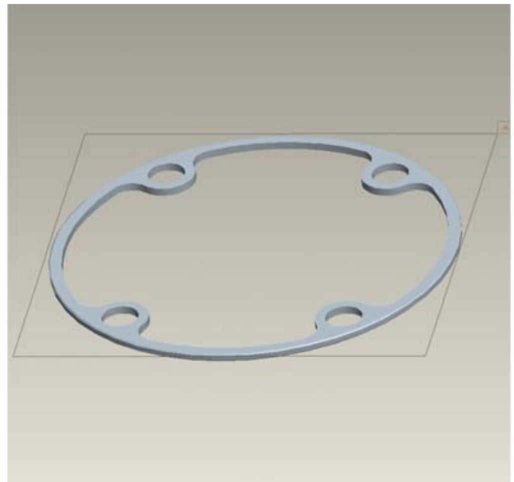

Figure 1: Piston Shim

squish volume present in the stock compression ratio. Figure 2 displays a comparison on the stock compression ratio configuration to that of the increased compression ratio.

Fuel injector nozzle design along with the pilot fuel cetane number were held constant during this experiment. By holding the previously mentioned variables constant, characteristics of the pilot fuel parameters were easily identified along with the effect of compression ratio on the ignition system. It is important to note that the fuel injector nozzle used during testing is a 3-hole design and evolved from analysis and testing conducted using an off-the-shelf Delphi 6-hole injector. The 6-hole fuel injector was designed for use in a European production Diesel fueled Ford Focus. The spray pattern created by the 6-hole fuel injector caused impingement of the pilot fuel on both the top of the piston and the surface of the head. In order to completely optimize the pilot ignition system, the fuel injector nozzle was redesigned to correct the impingement issues.

TESTING PROCEDURE

In order to carry out the optimization testing, a "response variable" *q* was created which consisted of both brake specific NO_x emissions and Total Modified Fuel Consumption (TMFC) components. TMFC represents the combined fuel consumption of

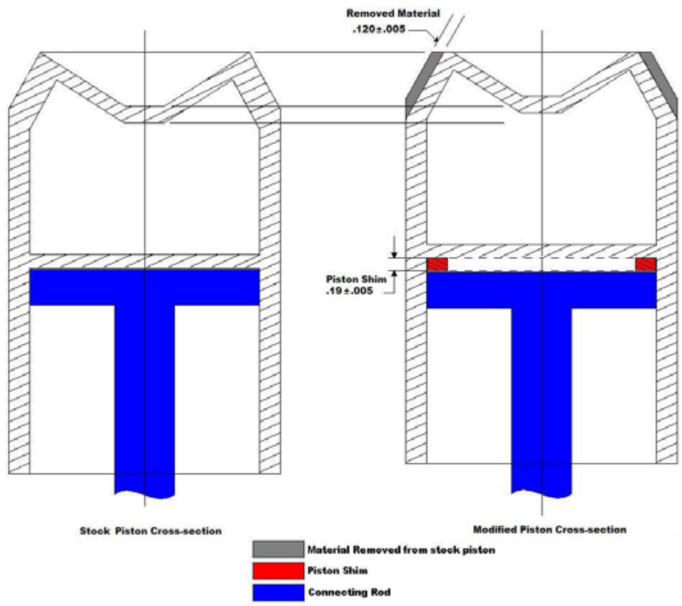

Figure 2: Comparison of Stock and Modified Piston

pilot fuel and natural gas, on an energy basis, with a penalty of 5 on the pilot fuel as shown in Equation 1. The penalty assessed to the pilot fuel accounts for the additional costs associated with the pilot fuel, including storage and delivery. Values of the brake specific NO_x and TMFC are normalized against reference values obtained during previous testing at similar engine operating conditions. Equation 2 displays the response variable *q* to be optimized.

$$TMFC = BSFC_{ng} + 5BSFC_{pilot}$$

Equation 1: Total Modified Fuel Consumption

$$q = \left(\frac{BS\_NO_x}{BS\_NO_{x\_ref}} + \frac{TMFC}{BSFC_{ref}} \right)$$

Equation 2: Test Variable q

At each subsequent boost level, a base three dimensional text matrix was created consisting of the three independent test parameters:

- Pilot fuel delivery pressure
- Pilot fuel quantity
- Pilot injection timing

The base test matrix consists of a center point, along with eight additional points, obtained by varying the three test parameters in positive and negative steps to acquire data at the corners of the test cube. At each data point, the response variable *q* was evaluated.

Upon completion of the test cube a statistical technique was used to create a vector that pointed in the direction of minimum response variable. The vector is followed until a local optimum is located. Upon identification of the local optimum an additional test matrix was created and the experiment was repeated. This procedure was repeated until a global optimum was achieved. The optimization technique utilized is referred to as the Design of Experiments technique. More details on this technique are provided in other work [1].

Upon completion of the low compression ratio testing, the GMV-4 test engine was modified to a medium compression ratio of 9.48/8.75:1 and the optimization procedure was repeated. Optimization testing at the medium compression ratio assessed a penalty of 10 to the diesel fuel along with an additional penalty of 1.5 to the BSFC term within the response variable equation.

TESTING RESULTS

Results of the optimization testing on the micropilot ignition system are displayed in Table 2 for a variety of boost levels and compression ratios. Optimum pilot fuel quantities generally increased with increased boost levels while pilot pressure continued toward lower pressures. Following location of the optimal micropilot parameters, combustion stability and emissions data were measured at the optimal settings.

Figures 3 through 8 compare various emission constituents and combustion stability of the stock spark ignition system against the micropilot ignition system at the stock compression ratio. Medium compression ratio testing resulted in similar trends and values as the stock micropilot

Table 2: Optimized Micro-pilot Parameters

	Stock Compression			Medium Compression		
Boost (in.Hg)	Pilot Pressure (psi)	Inj. Timing (BTDC)	Inj. QTY (µL)	Pilot Pressure (psi)	Inj. Timing (BTDC)	Inj. QTY (µL)
14.5	3600	13	16	4200	11.5	6
16.5	4200	11	13	4200	11	7
18.5	4200	11	16	4200	10	13
Lean Limit	4200	11	24	4200	10	24

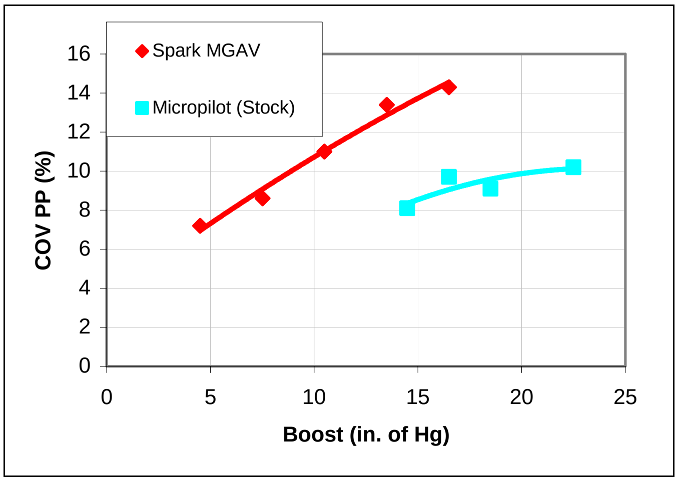

Figure 3: COV PP vs. Boost

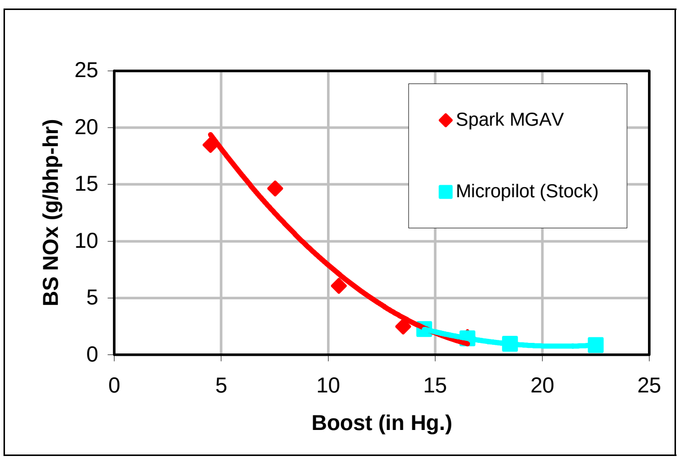

Figure 4: BS NOx vs. Boost

ignition system except for the case of BSFC, shown in Figure 9. As expected, a significant reduction in fuel consumption was encountered during the medium compression ratio testing.

Figure 3 presents Coefficient of Variation of Peak Pressure (COV PP) versus boost. The COV PP is the standard deviation of peak pressure expressed as a percent of average peak pressure.

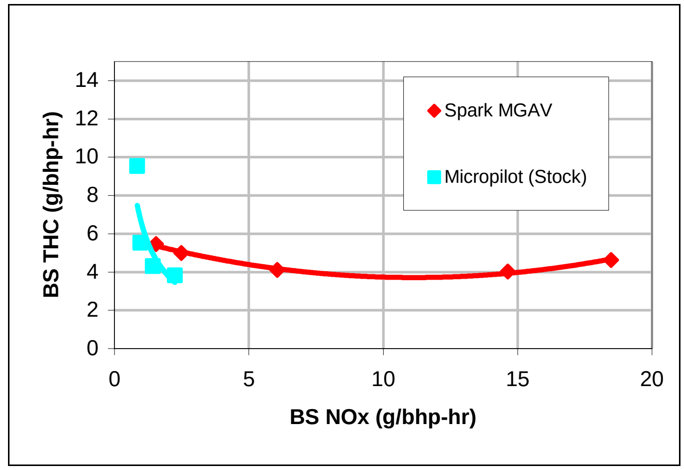

Figure 5: BS THC vs. BS NOx

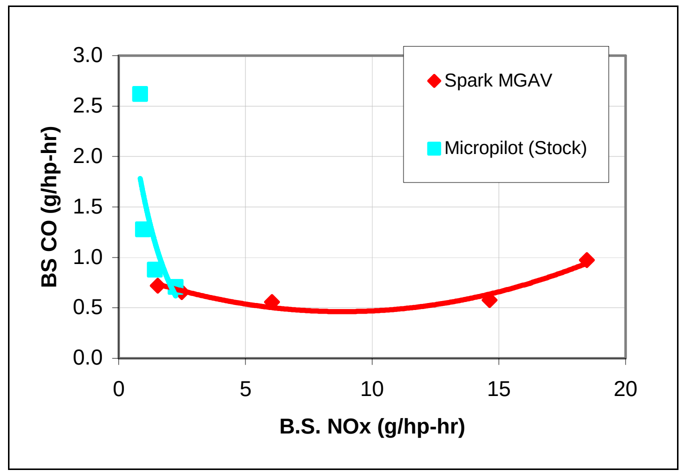

Figure 6: BS CO vs. BS NOx

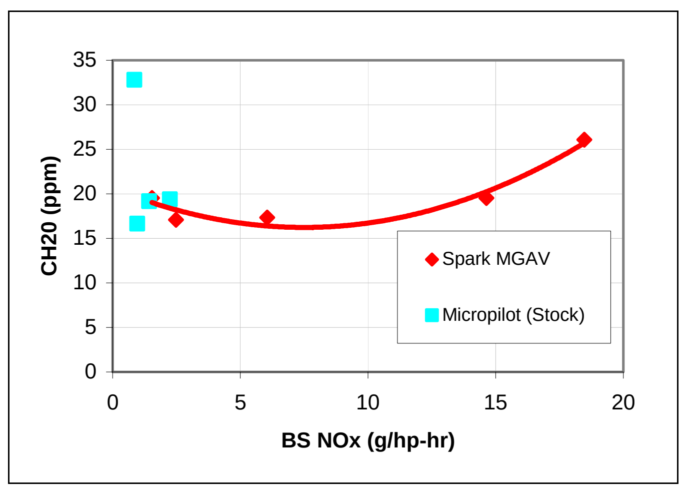

Figure 7: CH20 vs. BS NOx

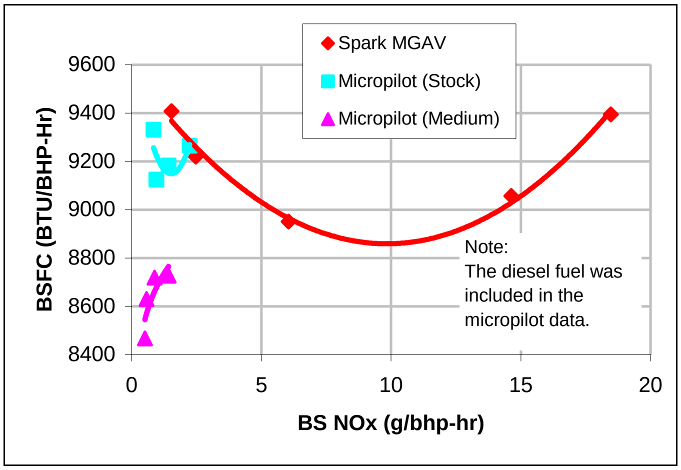

Figure 8: BSFC vs. BS NOx

This data shows that the micro-pilot ignition system significantly reduces combustion variability for the same boost. The lean limit of engine operation was significantly extended from the standard spark ignition system. Defining the lean limit of operation to be a value of the coefficient of variation of peak pressures exceeding 10%, the lean limit of operation was extended by approximately 12" of Hg. At the stock lean limit of 10" of Hg, emissions of nitric oxides were approximately 7 g/bhp-hr compared to <1 g/bhp-hr with micropilot ignition at 18.5" of Hg.

NOx emissions for the two configurations essentially fall on the same curve when plotted versus boost (Figure 4). Figure 4 shows a dramatic decrease in NOx emissions with increasing boost. This can be explained by the assertion that NOx formation is strongly related to bulk temperature, which is heavily influenced by trapped mass. The trapped mass in the cylinder is proportional to boost.

Figures 5-8 are cross-plots versus NOx examining products of partial combustion and Brake Specific Fuel Consumption (BSFC). The engine was not tested with micropilot ignition at low boost, high NOx conditions. In the boost range 14-17 "Hg a comparison can be directly made. In general products of partial combustion are lower, with the exception of one CO point and one CH2O point.

It appears that no additional net hydrocarbon emissions were created from the micropilot ignition system as a result of the diesel pilot fuel. This is encouraging since diesel fuel would be a volatile organic compound (VOC) emission. As shown in Figure 5, the brake specific hydrocarbons were actually reduced at some points below the spark ignition system. This is most likely a result of more extensive flame propagation due to the multiple ignition sites provided by the pilot fuel.

CONCLUSION

The micropilot fuel ignition study showed extremely promising results for the development of a commercially available retrofit technology for implementation on large bore natural gas engines. Combustion stability was considerably improved from traditional spark ignition systems along with the reduction of fuel consumption and various emissions constituents. Additionally, the lean limit of engine operation was significantly improved from the stock ignition system.

The minimum pilot fuel quantity required was 16 µL in the stock compression ratio configuration, contributing to 1% of the total fuel energy. In the medium compression ratio testing, the minimum pilot fuel quantity required was further reduced to 6 µL. This is about 1/3 % of the total fuel energy.

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