DEVELOPMENT AND PERFORMANCE ANALYSIS OF AN ADVANCED COMBUSTION CONTROL SYSTEM ON A FUEL-ADMITTED HIGH-SPEED NATURAL GAS ENGINE

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ABSTRACT

Given the drive for simultaneous reductions in both engine exhaust emissions and brake-specific fuel consumption, the operation of fuel-admitted, high-speed natural gas engines increasingly demands the application of enhanced combustion control technologies. Doing so allows for engine lines with significant and long-term service in gas compression and power generation to be modernized and operated in an environmentally responsible and cost-effective fashion.

This paper provides an overview of the joint development of a suite of technologies aimed at delivering on both goals – inclusive of the application of advanced fuel delivery/ignition systems and strategies and other engine-related modifications. Documented engine and emissions performance results are reviewed with the goal of providing a comprehensive understanding of the current and future impact of these technologies in meeting both the emissions and efficiency performance targets.

BACKGROUND

The aim of this paper is to familiarize the reader with the current and future potential for application of advanced combustion control technologies on fuel-admitted, high-speed natural gas fueled engines. Today's, often demanding, requirements for lower exhaust emissions and higher thermal efficiencies from reciprocating gas engines is driving development of new technologies capable of extending the operating life of legacy equipment. The research explained herein covers several of these technologies including electronic pre-combustion chamber control valves, electronic speed governing, and electronic air-fuel ratio control. Additionally, an introduction will be made to currently ongoing research which offers the potential for further enhancing machine operation.

The test engine chosen to evaluate these technologies is a remanufactured and heavily modified White-Superior 6GTL. The remanufacturing and modification is completed by EnDyn after which the engine is known as a 6GTLX. The basic 6GTL engine is a turbocharged, 4-stroke/cycle gas engine, with mechanical port-fuel admission. The 6GTLX modifications from a standard 6GTL include an oversized turbo-charger, new cylinder heads (inclusive of stoichiometric pre-combustion chambers), new camshaft, and improved inlet air cooling system – a typical 6GTLX engine layout is shown in Figure 1. The obvious goal of these modifications is to lower the exhaust emissions to required levels while maintaining acceptable performance. This goal is realized with the standard 6GTLX engine readily achieving sub-2g/bhp-hr NOx emission levels. The 6GTLX unit being tested is a 10.00” bore, 10.50” stroke 6-cylinder with the following ratings: 825bhp @ 900rpm & 146.7 psi BMEP, with a normal speed range between 600-900rpm. While the performance and emission levels of the current generation of GTLX and other high-speed fuel admitted engines meets the needs of today, the research preformed aims to enable the continued service of this type of machine into the future.

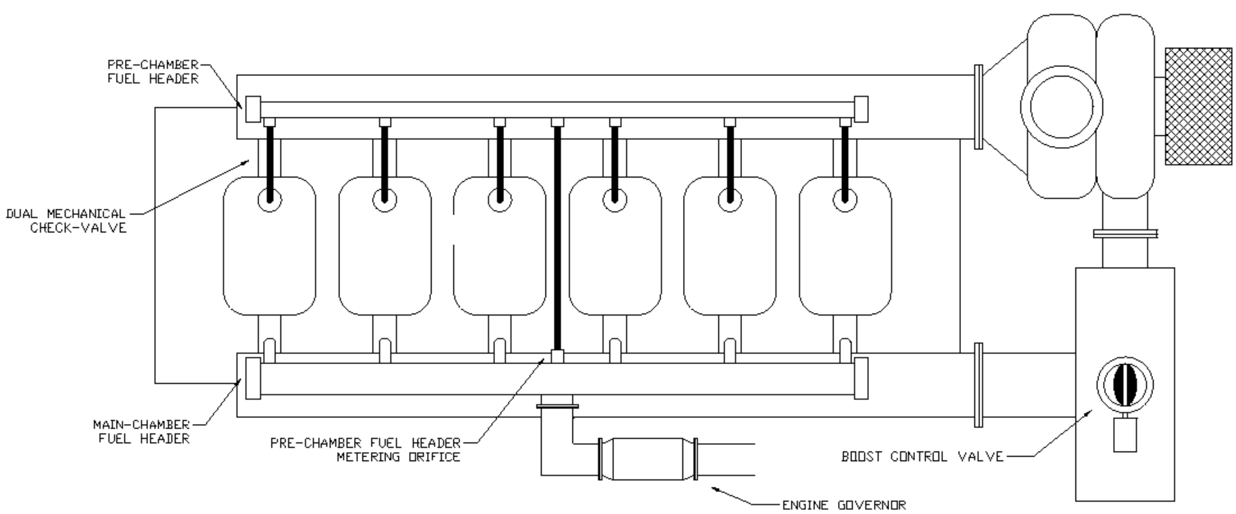

FIG. 1 – TYPICAL 6GTLX CONFIGURATION

INTRODUCTION AND SYSTEM TOPOLOGY

The first advanced technology explored in this paper is the application of electronic pre-combustion chamber control valves. The valve chosen for this research (Figure 2) exhibited a number of important characteristics inclusive of precise metering of fuel delivery, rapid actuation time, and the ability to survive direct combustion pressure. The application of this valve and its corresponding controller allow for precisely metered and positioned fueling events in the engine's pre-combustion chamber – this offers several opportunities to enhance engine operation. The first benefit of this technology comes in the form of precise fueling of the pre-combustion chamber leading to overall improvements in engine combustion stability and main-chamber air-fuel ratio formation. The next benefit of the electronic pre-chamber fuel control comes in the form of controlling the amount of fuel delivered to the pre-chamber independent of the main-chamber fueling. Lastly, the timing of the fueling event can be varied, leading to control over both the dispersive properties of the pre-chamber fueling and pre-chamber scavenging opportunity. While each of these benefits is itself an area of potential improvement over conventional, mechanical pre-chamber fuel systems, together they offer the ability to control pre-combustion chamber air-fuel ratio and pre-chamber influenced main-chamber fuel stratification.

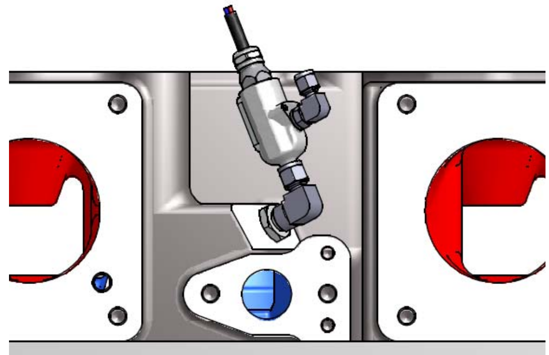

FIG. 2 – PRE-CHAMBER FUEL VALVE IN 6GTLX CYLINDER HEAD

The next technology employed in this research is electronic speed governing. Given the 6GTLX uses a mechanical port-fuel admission fuel system the engine governor chosen for this test was a voice-coil actuated integrated speed control. This type of governor is essentially an electronic fuel pressure regulator with integrated engine speed measurement that controls the fuel pressure in the engine's main fuel header, and thus fueling to engine cylinders. While this type of governor has been used for some time in similar service, it is important to mention as it is part of the larger system solution explained in this research. The consistency of the electronic governor is essential to low emission / high-performance operation as any instability in the engine governing could easily lead to masking of any improvement offered in other system components. It is important to mention that in the standard 6GTLX configuration pre-chamber fuel header

FIG. 3 – ELECTRONIC ENGINE GOVERNOR

pressure is slaved to main chamber fuel pressure and thus the engine governor – the test configuration for this research operates the pre-chamber fuel header at a fixed pressure, independent of main-header fuel pressure as can be seen in Figure 4.

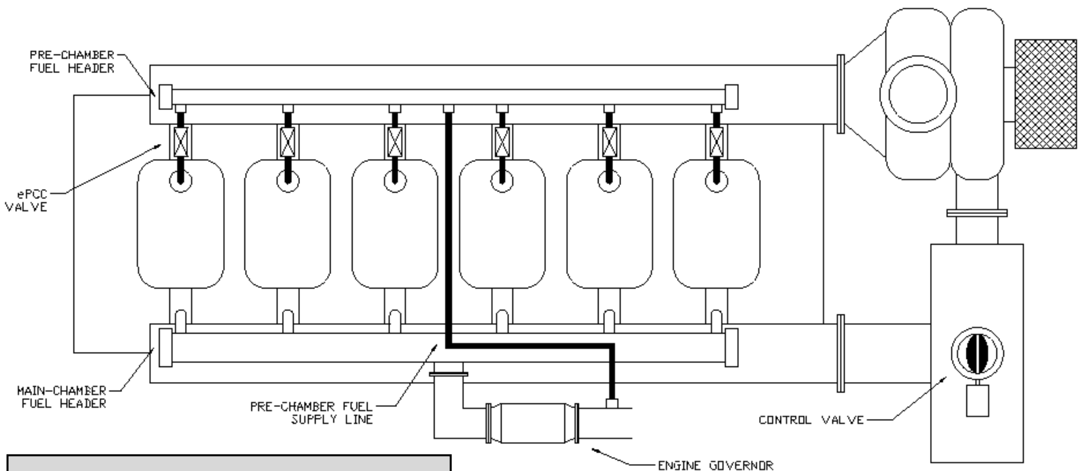

FIG. 4 – 6GTLX CONFIGURATION AS TESTED

The last major component of this advanced combustion control system is an electronic air-fuel ratio control device. The typical configuration of the 6GTLX engine uses a control valve located on the inlet of the aftercooler housing which vents compressed air to atmosphere allowing control of the air manifold pressure – this control valve arrangement can be seen in Figure 5. While this configuration is not standard compared to a more traditional exhaust wastegate, it has proven a robust solution for the typical application of the 6GTLX where immediate turbocharger energy can be advantageous in combating rapid load fluctuation. This is most evidently illustrated by the 6GTLX's success in providing additional engine stability in the demanding applications like gas compression. Control of the engine's air-fuel ratio is accomplished with a pneumatic actuator driving the control valve through an I/P converter connected to the air-fuel ratio control. The control strategy employed is the

FIG. 5 – 6GTLX BOOST CONTROL VALVE

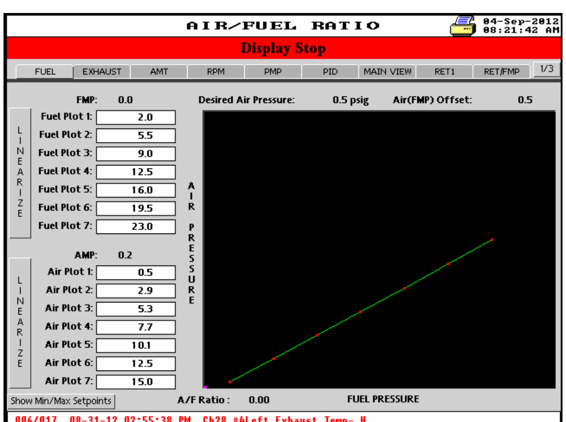

FIG. 6 – AIR/FUEL CONTROL APPROACH

typical open-loop map-based approach shown in Figure 6. While the 6GTLX application often employs a proprietary controller for air-fuel ratio control, the research engine's air-fuel ratio was controlled with a PLC located in the engine's primary control panel.

TEST RESULTS

The experimental 6GTLX engine used in this research was located at EnDyn's primary manufacturing facility in Alice, TX. Experimental data was taken in both late March, 2012 and early August, 2012 with repeatability of results demonstrated across the corresponding range in ambient conditions. The 6GTLX was tested utilizing the facility's water-brake dynamometer and data acquisition system, which has been successfully used in the past for similar types of research. Critical engine parameters such as temperatures, pressures, and flows were captured using the facilities data acquisition system which consists of a PLC-based control system and standard industrial grade instruments. It is of note to mention that the water-brake used in this test is not outfitted with a torque measurement system – the horsepower data obtained during the testing was calculated using the water differential temperature and flow. Engine exhaust emission levels were measured with a portable exhaust analysis system consisting of two (2) Testo exhaust analyzers and known calibration gases – regular verification & calibration of measurements was performed.

The testing regime for evaluating the effect of the combustion control system on the 6GTLX engine included sweeps of pre-combustion chamber fuel injection location and duration, however initial testing showed that bottom dead center (BDC) of the intake stroke was effective at a variety of conditions. Figure 7 depicts a typical control screen for the pre-chamber fueling system as it was configured for testing. Once the BDC timing position was chosen as a constant, data was taken over a sweep of injection timing durations and loads to determine the effect on engine operation - of particular focus was exhaust emissions and fuel consumption.

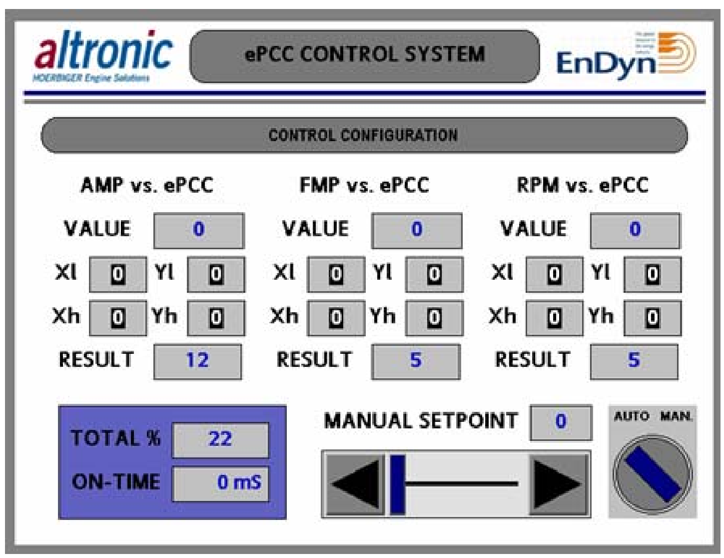

FIG. 7 – TYPICAL PRE-COMBUSTION CHAMBER FUEL CONTROL SYSTEM

The effect on engine NOx production as compared to baseline mechanical valve operation can be seen in Figure 8. At lower injection timings, an engine out NOx reduction of approximately 30% was realized over the conventional mechanical fuel system (as tested). This significant reduction in NOx production has been attributed to the consistency of fueling in both pre and main-chambers experienced when using the electronic pre-combustion chamber fuel valves.

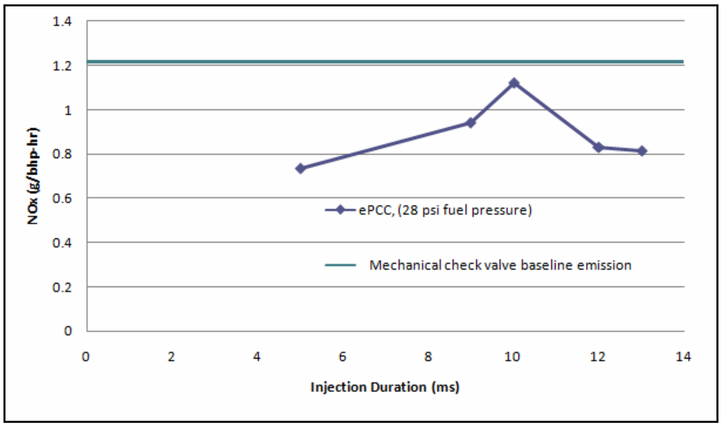

FIG. 8 – NOx PRODUCTION w/ELECTRONIC FUEL VALVE vs. BASELINE

In order to assure reliability of measurements and gain confidence in the results, the effects of mixture lambda variations on exhaust port temperatures, NOx and O_2 emissions levels were evaluated and are reported in Figures 9 and 10. Reducing fuel flow by 3%, increased lambda by 0.045 points which caused the average exhaust port temperature to increase by 3 ^{0}F (see Figure 9). These results are consistent with the expected reduction in combustion rates caused by the leaner lambdas.

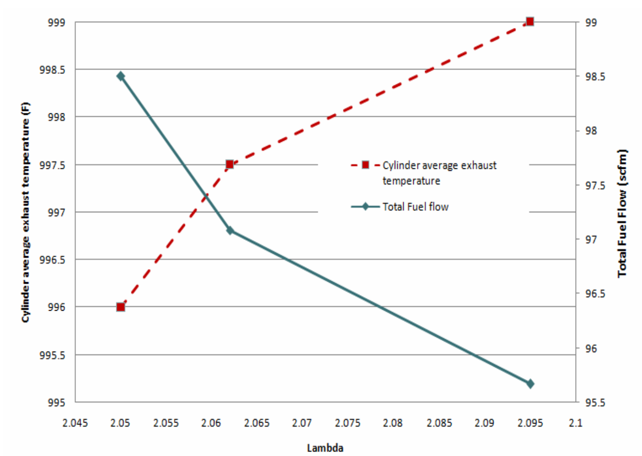

FIG. 9 – EGT & FUEL FLOW vs. LAMBDA w/ePCC

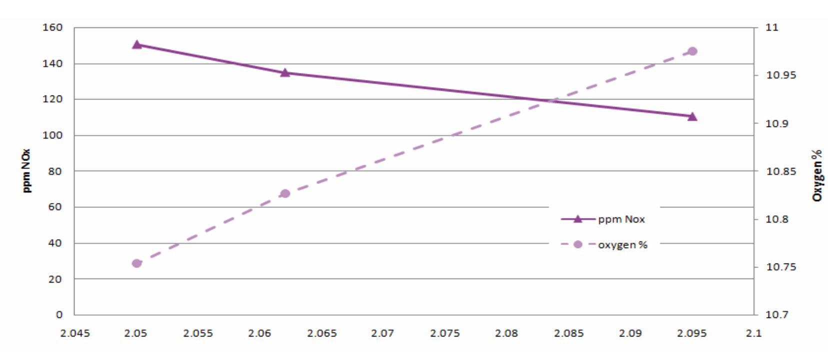

FIG. 10 – EMISSION LEVELS vs. LAMBDA w/ePCC

Also, from the emission data shown in Figure 10, the measured NOx range of 20 ppm and the measured O_2 range of 0.2% are consistent with the lambda range of 2.05 – 2.095 at which these measurements were taken.

Additional tests with the electronic pre-combustion chamber fuel valve and a conventional pre-combustion chamber were conducted to evaluate the novel concept of the two-stage pre-combustion chamber using a passive pre-combustion chamber (PPC) spark plug. The intent of the two-stage pre-combustion chamber is to minimize the volume of rich mixture that is burned, thereby reducing the total amount of NOx produced. This objective can be achieved by confining a rich mixture in the smaller PPC spark plug volume, while maintaining a leaner mixture throughout the fueled pre-combustion chamber.

The two-stage pre-combustion chamber tested consisted of the standard 6GTLX fuel-fed pre-combustion chamber and a passive pre-combustion chamber (PPC) spark plug. The intent of this test was to show a potential for further NOx reduction by simply replacing the conventional spark plug with a PPC sparkplug thus achieving effective combustion of leaner mixtures in the fueled pre-combustion chamber. Although no attempt was made to optimize this system, the PPC sparkplug (P1863DP-1) was installed with a 4 mm copper spacer allowing the PPC holes to align with the fueled pre-combustion chamber fuel port. A description of the pre-combustion chamber assembles is provided in Figure 11.

FIG. 11 – PRE-COMBUSTION CHAMBER ASSEMBLY – PRE-COMBUSTION CHAMBER w/J-GAP SPARK PLUG (top right) – TWO-STAGE PRE-COMBUSTION CHAMBER w/PPC SPARK PLUG (top left)

The test results comparing the two-stage pre-combustion chamber and the conventional configuration are outlined in Figures 12 and 13. It can be seen that leaner lambda (>0.1) and lower NOx (>20%) are achieved with this non-optimized two-stage pre-combustion chamber. This result is presumed to be due to the more effective burn of the leaner mixture within the pre-combustion chamber achieved with the flame jets of the PPC spark plug.

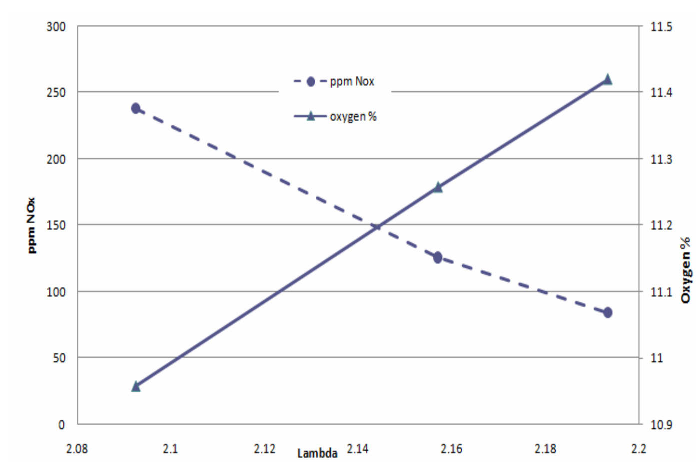

FIG. 12 – EMISSION LEVELS FOR TWO-STAGE PRECOMBUSTION CHAMBER w/ePCC & PPC SPARK PLUG

Optimization of the two-stage pre-combustion chamber system should result in very low NOx emissions. Based on a cursory analysis, it has been estimated that the PPC spark plug can operate the fueled pre-combustion chamber at a lambda of 1.5 or greater. In this situation, the NOx level of 0.7 g/bhp-hr achieved with the ePCC and conventional pre-combustion chamber could be theoretically reduced well below current levels (<0.5 g/bhp-hr) while maintaining engine combustion stability, power output and thermal efficiency. Additional testing is planned to explore this concept in much greater detail.

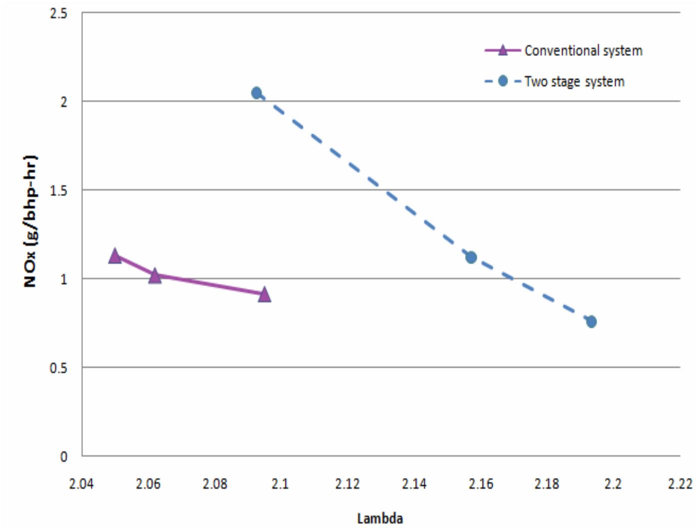

FIG. 13 – NOx COMPARISON BETWEEN CONVENTIONAL PRE-COMBUSTION CHAMBER AND A NON-OPTIMIZED TWO-STAGE PRE-COMBUSTION CHAMBER w/ PPC SPARK PLUG

CONCLUSIONS

An array of technologies including electronic speed governing, electronic air-fuel ratio control, and electronic pre-combustion chamber control valves were tested on the experimental 6GTLX engine at EnDyn. A systematic test approach was used to quantify the potential for lower NOx emissions. Results indicated that speed governing and air-fuel ratio control are critical to assure stable engine operation with lean mixtures at or below the 1.0 g/bhp-hr NOx level. Moreover, it was demonstrated that the electronic pre-combustion chamber control valves can effectively control the amount of fuel admitted and the timing of the fuel admitted to the pre-combustion chamber and can reduce the NOx emissions well below 1.0 g/bhp-hr. Additionally, the potential for achieving lower NOx emissions, in the range of 0.5 g/bhp-hr and lower, was demonstrated with a two-stage pre-combustion chamber. This configuration was realized by simply replacing the conventional spark plug used in the pre-combustion chamber with the PPC sparkplug. The lower NOx resulted from burning leaner air-fuel mixtures in the pre-combustion chamber.

RECOMMENDATIONS

In order to facilitate system optimization, improvements in the engine test bench should be pursued. In particular, the engine dynamometer should be equipped with a load cell to provide for direct torque measurements and combustion pressure transducers should be installed to directly monitor the combustion process. Optimization of electronic pre-combustion chamber control valves should then be conducted with the stoichiometric pre-combustion chamber, utilizing a conventional spark plug, and with the lean pre-combustion chamber, utilizing the PPC spark plug. Computational fluid dynamics (CFD) analysis of pre-combustion chamber and PPC geometries and electronic pre-combustion chamber control valve fueling strategies should also be planned prior to engine testing.

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