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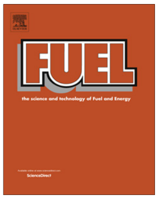

Full Length Article

Evaluation of operating parameters and fuel composition on knock in large bore two-stroke pipeline engines

John W. Ladd *, Daniel B. Olsen, Greg Beshouri [1]

Engines and Energy Conversion Laboratory, Mechanical Engineering Department, Colorado State University, 430 N. College Ave Fort Collins, CO 80524, United States

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A B S T R A C T

Legacy integral compressor engines are crucial to the operation of the North American natural gas pipeline network. Many of these engines are uncontrolled utilizing mechanical scavenging or light turbocharging. The engines typically operate between ~10 and 20 g/bhp-hr of NOx with a minimal knock margin. While suitable for typical pipeline gases, high ethane shale gas can erode the knock margin with the added risk of performance degradation and engine damage. Phase one of the project investigated the impact of variable fuel quality and determined which engine parameters (ignition timing, air manifold temperature, and trapped equivalence ratio) were most effective in preventing and controlling knock. Phase two of the project evaluated the ability of an accelerometer and a NOx emissions sensor to detect engine knock as well as the development of knock prediction models.

Testing confirmed elevated fuel ethane could induce continuous engine knock but ignition timing was the most effective method to mitigate engine knock, followed by trapped equivalence ratio. Air manifold temperature did not significantly affect knock onset. When properly tuned, a typical off the shelf accelerometer knock detection system could detect and protect against the onset of knock. Persistent knock lead to a steady increase in NOx production, but NOx values alone were inadequate to detect and protect against knock. The knock prediction models accurately predicted the onset of knock based on ignition timing, trapped equivalence ratio, and fuel composition, suggesting a fundamental relationship between operating parameters and engine knock.

1. Introduction

1.1. Drivers

Natural gas fuels are comprised of a wide range of components that vary by source, location, and time. These variations have a significant impact on the performance and emissions of natural gas engines. Fuel gas with high chemical energy content, low methane number, can lead to auto-ignition and many legacy engines do not have suitable knock detection and mitigation controls. The greater chemical energy in the shale gas is primarily caused by an increase in ethane content [1]. The legacy engines were designed to run on traditional mined natural gas content with ~5% ethane but shale gas can have upwards of 30% ethane [1].

PRCI sponsored a project, at the Colorado State University (CSU) Engines and Energy Conversion Laboratory (EECL), to determine the potential knock risk, identify appropriate remedial options, and evaluate detection techniques to prevent abnormal combustion for integral compressors with minimal engine controls operating at NOx levels between 10 and 20 g/bhp-hr. This project investigated the impact of variable fuel quality and determined which engine parameters (ignition timing, air manifold temperature, and trapped equivalence ratio) were most effective in preventing and controlling knock.

1.2. Typical reciprocating pipeline engine

There are three types reciprocating, large bore compression engines in use on the North American pipeline network: 2-cycle (stroke) lean-burn, 4-stroke lean-burn, and 4-stroke rich-burn, as specified by the EPA document AP-42 [2]. The focus of this work was to evaluate the knock characteristics of legacy 2-cycle (stroke) lean-burn engines.

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* Corresponding author at: Hoerbiger Engineered Solutions, 8448 N Sam Houston Pkwy West, Houston, TX, United States.

E-mail addresses: john.ladd@hoerbiger.com, johnladd34@gmail.com (J.W. Ladd), daniel.olsen@colostate.edu (D.B. Olsen), greg.beshouri@hoerbiger.com (G. Beshouri).

[1] Hoerbiger Engineered Solutions, 8448 N Sam Houston Pkwy West, Houston, TX, United States.

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Many of the legacy integral compressor engines are uncontrolled, meaning they lack air/fuel ratio control. Typically these engines operate at 10–20 g/bhp-hr NOx with a minimal knock margin. While suitable for typical pipeline gases, high ethane shale gas can erode the knock margin. For the purpose of this paper uncontrolled

Integral pipeline engines fall into the following broad categories: first generation mechanically scavenged engines which rely on reciprocating air pumps for their air supply, second generation engines fitted with early turbochargers generally sufficient to carry the design load with limited knock margin, and third generation engines with robust air/fuel ratio controls.

The first generation engines lack air/fuel ratio control and the air supply is proportional with engine speed, increasing and decreasing relative to engine speed with no dependence on torque requirements. Consequently, air/fuel ratio and NOx emissions can vary substantially.

The second generation of engines, the air supply is proportional to the power output. Typically, these "lightly turbocharged" engines can maintain relatively constant air/fuel ratio with varying torque and to a lesser extent with varying speed. The early turbochargers on these engines lack the excess performance to increase the air/fuel ratio and cannot maintain the knock margin as fuel quality changes.

The third generations of engines were necessary with the introduction of stringent emission regulations. To meet the new emissions requirements, more robust air/fuel ratio controls based on trapped equivalence ratio (TER) were implemented. These strategies were designed to maintain NOx emissions as speed, torque and air manifold temperature (AMT) vary. With real time fuel speciation, these strategies can maintain NOx emissions as the fuel quality changes. These same TER strategies should maintain knock margin as speed, torque AMT and fuel quality changes.

This current work focuses on characterizing the change in knock margin as fuel quality changes for pump scavenged and lightly turbocharged engines.

1.3. Off the shelf knock detection

In the automotive and high speed stationary engine market there are several accelerometer-based knock detection systems available, but little work has been done to develop the technology for slow speed integral compressors. The knock dynamics between different classes of engines are very similar; therefore, an accelerometer based knock detection system would be viable for the integral compressor market.

The existing technology mounts an accelerometer directly on the cylinder head and isolates the combustion vibration frequencies to determine the presence of combustion abnormalities. The external processing device is interfaced with the engine controls, to retard timing or reduce torque when knock is detected.

The current systems need to be tuned to the specific engine to filter out extraneous vibrations and isolate the engine's specific knock frequency. The expected knock frequency is defined by Heywood as time it takes a pressure wave propagating at the speed of sound to travel twice the bore [3]. Tuning includes but is not limited to, determining ideal mounting location, altering expected knock frequency to account for cylinder wall thickness, and adjusting the detection frequency range. Once the knock devices are tuned, they are very effective at protecting the engine from knock damage.

2. Materials and methods

The testing was carried out using a 4-cylinder Cooper-Bessemer GMV-4 large bore natural gas 2-stroke cycle engine, typical of early generation pipeline engines. A picture of the engine can be seen in Fig. 2. The engine is a slow speed (300 rpm) engine with a 14″ bore and 14″ stroke. The engine has direct fuel injection, utilizing the original cam-driven mechanically actuated fuel valves. It is loaded with a computer-controlled, water brake dynamometer to provide precise load control. The GMV-4 is equipped with an Altronic CPU-XL VariSpark ignition system. Air supply for the engine is provided via a turbocharger simulator. The turbocharger simulator used a Gardner Denver screw compressor and a backpressure valve. Through LabVIEW control, the exhaust manifold pressure can be controlled to simulate the backpressure for any turbocharger or mechanically scavenged set point.

The ignition system was operated in the CPU 2000 single strike emulation mode. Ignition timing was adjusted to maintain a location of peak pressure of 18° ATDC, typical for this engine configuration. For this testing, the engine was operated at a GMVA rating of 500 bhp, which corresponds to a brake mean effective pressure (BMEP) of 77 psi.

Engine TER control was based off a typical control strategy employed on similar field engines outlined in a report by Advanced Engine Technologies Corporation [4]. The TER controller incorporated a scavenging model to account for the differences between air and residual combustion products.

The GMV-4 engine is typically operated on pipeline quality natural gas but for this project an ethane blending system was implemented to control the fuel quality. The ethane blending system consisted of three main parts, the bottles, the manifold, and the injection valve with mass flow feedback control. The ethane gas bottles were pressurized to ~470 psi and connected to three regulators to give adequate ethane flow.

Fig. 1. Cooper bessemer GMV-4 at the CSU EECL.

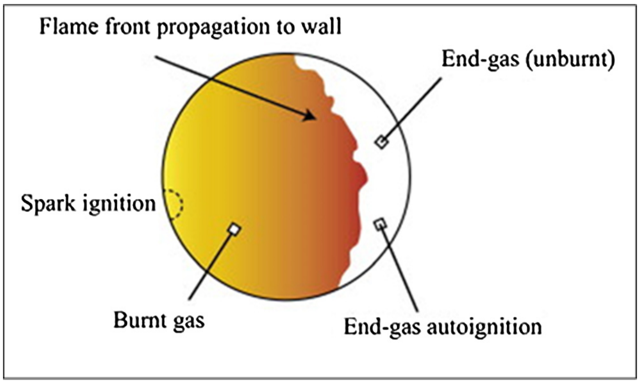

Fig. 2. End-gas auto-ignition (knock) diagram [9].