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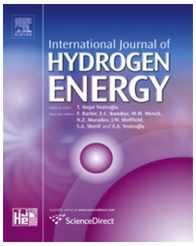

Engine knock and combustion characteristics of a spark ignition engine operating with varying hydrogen and carbon monoxide proportions

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ABSTRACT

Varying proportions of hydrogen and carbon monoxide (synthesis gas) have been investigated as a spark ignition (SI) engine fuel in this paper. It is important to understand how various synthesis gas compositions effect important SI combustion fundamentals, such as knock and burn duration, because in synthesis gas production applications, the compositions can vary significantly depending on the feedstock and production method.

A single cylinder cooperative fuels research (CFR) engine was used to investigate the knock and combustion characteristics of three blends of synthesis gas (H_2/CO ratio); 1) 100/0, 2) 75/25, and 3) 50/50, by volume. These blends were tested at three compression ratios (6:1, 8:1, and 10:1), and three equivalence ratios (0.6, 0.7, and 0.8).

It was revealed that the knock limited compression ratio (KLCR) of a H_2/CO mixture increases with increasing CO fraction, for a given spark timing. For a given equivalence ratio and spark timing, a 50%/50% H_2/CO mixture produced a KLCR of 8:1 compared to a 100% H_2 condition, which produced a KLCR of 6:1. The burn duration and ignition lag is also increased with increasing CO fraction. The results from this work are important for those considering using synthesis gas as a fuel in SI engines. It reveals that although CO is a slow burning fuel, higher CO fractions in synthesis gas can be beneficial, because of its increased resistance to knock, which gives it the potential of producing higher indicated efficiencies through the utilization of an engine with a higher compression ratio.

1. Introduction

Hydrogen has been dubbed by many to be the fuel of the future. The production of hydrogen, however, remains one of the many fundamental technical hurdles before this is possible. Unlike most other elements, hydrogen cannot be mined, but must be extracted from other more complex molecules, such as hydrocarbons. Many of these hydrogen production methods, however, produce not only hydrogen, but also carbon monoxide, carbon dioxide, nitrogen, and water. The combination of these produced gases is known as synthesis gas or syngas, with the fuel component typically comprised of a mixture of H_2/CO. Syngas can be produced from a variety of feed stocks ranging from fossil coal to renewable biomass. This allows for syngas production to be tailored to a localized resource. The problem with having a variable feedstock and variable production methods is that the syngas composition can also vary significantly.

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There have been investigations of hydrogen supplementation in compression ignition (CI) engines and hydrogen fueled spark ignition (SI) engines; however there is little published work on the utilization of varying blends of synthesis gas in either combustion regime. Understanding how a varying H_2/CO ratio (syngas fuel component) can affect the combustion fundamentals in an internal combustion engine (ICE) is a critical first step in characterizing a syngas fuel. These combustion fundamentals for SI engines include, but are not limited to the fuel's resistance to knock, its burn duration, and the flame development time or ignition lag.

The knock resistance of an SI engine fuel is a key parameter which limits the compression ratio, hence limiting overall thermodynamic efficiency. Engine knock in SI engines occurs when the unburned fuel-air mixture, called the end gas, autoignites ahead of the flame front, which is meant to consume the mixture. This phenomenon is believed to result from an increase in the temperature and pressure of the end gas region. The temperature and pressure of the end gas region are constantly changing because of piston motion and also because of the passing flame front which causes end gas compression. In some cases, such as for engine knock, a sufficient temperature and pressure threshold in the end gas is reached, thus causing the fuel energy in the end gas region to be liberated rapidly. This produces high frequency pressure oscillations within the combustion chamber, along with an audible knocking sound outside of the engine, which can be damaging to the engine if severe enough and left uncontrolled. A significant amount of work has been dedicated to engine knock [1–4] and more specifically engine knock with gaseous fuels [5–8].

Li et al. investigated the knock and combustion characteristics of methane, hydrogen, carbon monoxide, and their binary mixtures [9]. They found the knock limited compression ratio (KLCR) of dry CO to deteriorate significantly in the presence of small amounts of CH_4, H_2, or even H_2O. These results of carbon monoxide's superior knock resistance over hydrogen and its knock resistance degradation with water was also reported by Anzilotti et al. [10].

Szwaja et al. investigated combustion knock of hydrogen and gasoline in SI engines [11]. They used various methods of knock detection ranging from in-cylinder pressure, to piezoelectric accelerometers. It was determined that the knock detection techniques used for gasoline engines are also applicable with hydrogen SI engines, with some modifications.

Shrestha et al. investigated the effect of diluents on the knock rating of gaseous fuels [12]. Their knock detection method utilized the third derivative of the in-cylinder pressure with varying blends of methane and hydrogen [13,14]. With these blends they added either carbon dioxide or nitrogen, both of which increased the knock resistance of the fuels. Of the two diluents, carbon dioxide increased the knock resistance considerably more than nitrogen [12].

The focus of this work was to determine the knock limit of varying H_2/CO ratios in an SI engine using a quantifiable knock detection method, which utilizes the data generated from the filtered in-cylinder pressure traces. This paper also describes the combustion characteristics of an SI engine operating on varying H_2/CO blends, by measuring the burn duration, rapid burn angle, and ignition lag time of these fuels.

2. Experimental setup

2.1. *Engine test stand*

A single cylinder, four-stroke, SI Cooperative Fuels Research (CFR) octane engine was used for this testing. This engine is typically used for liquid fuel octane testing under ASTM D2699 and D2700. A key design feature of this engine, which makes it ideal for knock testing, is the variable compression ratio mechanism which allows the compression ratio to be adjusted from 4:1 to 18:1 while the engine is firing.

The engine was modified from its original configuration to accommodate electronic gaseous fuel injection and spark timing control. Two Quantum PQ2-3200 fuel injectors were used to inject the H_2 and CO gases roughly 4 cm from the intake port. The fuel injection and spark timing were controlled electronically via a MoTeC M800 controller. The gaseous fuels were supplied from compressed gas cylinders (>99% purity) of H_2 and CO, and the flow rates were measured via Alicat m-series mass flow meters. A Merriam 50MW20-2 laminar flow element was used to measure the air flow into the engine. A synchronous motor/generator system was used to load the engine and maintain a constant engine speed of 900 RPM.

In-cylinder pressure was measured using a Kistler 6125B pressure transducer with a Kistler 5010 charge amplifier. The experiments consisted of two parts; 1) knock testing and 2) combustion testing. For both portions of the testing, a National Instruments 6036e DAQ card was used. For the knock tests, a sampling frequency of 200 kHz was used with the CPU internal clock determining the acquisition frequency. This high sampling frequency, corresponding to an in-cylinder pressure data point of roughly once every 0.027 crank angle degrees (CAD), was necessary to resolve the high frequency pressure oscillations that were encountered during engine knock. An indexing signal (once per revolution) from a US Digital HD25 optical encoder was used to trigger the data acquisition. For the combustion testing, the counter signal from an optical encoder (1000 counts per revolution) was used as an external clock for the DAQ system, which corresponded to an in-cylinder pressure data point every 0.36 CAD. The heat release rate (HRR) analysis was conducted using a single zone model neglecting heat transfer to the cylinder walls.

2.2. *Testing procedure*

For all test conditions, three ratios (by volume) of H_2/CO were investigated; 1) 100%/0%, 2) 75%/25%, and 3) 50%/50%. Initial engine warm-up consisted of the engine operating on 100% H_2 at an equivalence ratio (EQR) of 0.5 and a compression ratio (CR) of 6:1, until all temperatures stabilized.

The knock testing was started at an engine CR at 6:1 and the spark timing (ST) was maintained at -12 CAD after top dead center (ATDC) throughout. The EQR was then increased until the onset of knock was detected. The onset of knock was quantified by a knock index (KI), which was determined by the peak to peak amplitude fluctuation from the filtered in-cylinder pressure trace. If the KI exceeded 0.35 bar in more than 20% of the sampled data cycles, then the condition was