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Experimental study of lean spark ignition combustion using gasoline, ethanol, natural gas, and syngas

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ABSTRACT

In the development of internal combustion engines, engineers and researchers are facing the challenge of improving engine efficiency while reducing harmful exhaust emissions. Previous research has shown that lean combustion is one of the viable techniques that can improve engine efficiency while effectively reducing exhaust emissions. Lean burn engines operate at low burned gas temperatures and can achieve high thermal efficiency based on favorable mixture thermodynamic properties. However, under high dilution levels, a lean misfire limit is reached where the combustion process becomes unstable and incomplete combustion starts to occur. Instability significantly affects engine efficiency, driveability, and exhaust emissions, which limit the full potential of lean burn engines. The lean misfire limit is not only dependent on engine design but also on fuel properties. Therefore, fuels that are conducive to lean combustion can provide the opportunity for enhanced efficiency and reduced emissions. Spark ignited (SI) combustion with conventional gasoline has shown to have relatively narrow range of fuel-air equivalence ratio; therefore, it is desired to explore the lean limit of SI combustion by using alternative fuels, which can also contribute to the reduction of greenhouse gas emissions from transportation and power generation.

Experiments were conducted on a Cooperative Fuel Research (CFR) engine with varying fuel-air equivalence ratio (φ) to assess the engine performance and emissions with three alternative fuels, natural gas, ethanol, and syngas, at compression ratio of 8:1 and engine speed of 1200 rev/min. Equivalence ratio was varied by decreasing the mass of fuel while keeping the mass of air the same. The lean misfire limit was defined as the equivalence ratio where the CoV of IMEP across multiple consecutive engine cycles was greater than 5%. It was found that syngas can maintain stable combustion at extremely lean conditions and has the lowest lean misfire limit. Natural gas combustion achieved a lower lean misfire limit than gasoline and ethanol. Gasoline and ethanol had similar lean misfire limits, but it was found that gasoline helped the engine to achieve higher load and fuel conversion efficiency compared to the three alternative fuels.

1. Introduction

Spark ignited engines are the most common power source for light-duty vehicles and some small power equipment. With increasing oil prices, depleting fossil fuel reserves, and growing concerns of environmental effects from burning fossil fuels, alternative fuels can offer solutions for sustainable future transportation and power generation. Although SI engines have been widely used in commercial applications, their thermal efficiency has been limited in part by low compression ratio and stoichiometric mixture composition. Lean operation can offer significant thermal efficiency benefits due to high ratio of specific heats (γ) and low heat transfer losses, while low burned gas temperatures reduce NOx emissions. Although lean burn SI engines can benefit from improved engine efficiency and reduced emissions, certain challenges need to be overcome before the full potential of lean burn SI engines can be realized. As the fuel-air mixture becomes lean, the heat release is reduced and the laminar flame speed decreases, resulting in increased burn duration, which in turn may offset any thermal efficiency benefits [1,2]. Also, at very lean conditions combustion becomes unstable and the ignitability of the fuel-air mixture is poor, leading to incomplete combustion or misfire, which greatly affects emissions and thermal efficiency [3,4]. This lean limit can be defined as the equivalence ratio at which the Coefficient of Variation (CoV) of Indicated Mean Effective Pressure (IMEP) is above 5%. The lean misfire limit is not only dependent on engine design, but also depends on fuel-air mixture properties such as the laminar flame speed, ignition energy requirement, and the latent heat of vaporization. Therefore, a fuel which enables very lean combustion can provide the opportunity for enhanced efficiency and reduced emissions. Gasoline SI combustion has been shown to have a relatively narrow lean operating range [1], but alternative fuels such as ethanol, natural gas, and synthesis gas (syngas) can extend the lean limit of SI engines based on their favorable properties. In order to investigate the extension of the lean misfire limit using alternative fuels, it is important to understand their combustion characteristics, and how their different fuel properties can promote lean mixture ignition and flame development.

Several studies have focused on SI engine operation with alternative fuels and have compared them with conventional gasoline. *Natural gas* is considered the most common and promising alternative gaseous fuel and is primarily composed of methane at concentration that ranges

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between 85 and 97% by volume [5]. It has high H/C ratio (~3.8), which results in lower CO_2 emissions [6,7], and a high research octane number (RON~130), which enables operation at high compression ratio for increasing thermal efficiency and power output [8]. It also has a lower lean flammability limit than gasoline, which promotes lean ignition in SI engines [2]. The lower heating value (LHV) of natural gas is slightly higher than gasoline, however the gaseous nature of the fuel can result in lower engine volumetric efficiency and thus power output [5], caused by the gas displacing intake air and the lack of evaporative cooling compared to liquid fuels. In addition, SI combustion with natural gas has shown lower heat release rate than gasoline combustion, because of the lower laminar flame speed of natural gas under high temperature and pressure conditions, which increases the burn duration and thus heat transfer loss, resulting in lower thermal efficiency [9].

Synthesis gas or "syngas", is a mixture that consists mainly of hydrogen and carbon monoxide and can be formed at different ratios. Syngas can be produced from natural gas, coal, biomass, or hydrocarbon feedstock. Typical LHV values of syngas are lower than natural gas and hydrocarbon fuels, due to the lower density of hydrogen and carbon monoxide [10,11]. Hydrogen has the highest laminar flame speed and lowest ignition energy among gaseous fuels, and also has a high Research Octane Number (RON) (~120) [12–14]. Since syngas can be composed mainly of hydrogen, running syngas in SI engines is expected to lower the lean misfire limit, which reduces the duration of flame development and flame propagation, and thus improve the engine lean burn capability compared to conventional gasoline. However, syngas also affects the engine volumetric efficiency due to its gaseous state, and typically has a lower heating value compared to liquid fuels. Emissions formation can benefit from using syngas since there is no hydrocarbon content in the fuel. In addition, by enabling lean combustion the burned gas temperatures can be kept below the NOx formation threshold.

Ethanol has traditionally been used as a sole fuel or in blends with gasoline for use in SI engines. Since ethanol can be produced from sugar cane, corn, or wheat it has been used extensively as an alternative fuel or additive to gasoline in the United States, Brazil, and Europe. Ethanol has higher RON than gasoline (~113), which enables the use of higher compression ratio with associated efficiency and performance benefits [15]. Engine volumetric efficiency can be improved due to the higher latent heat of vaporization of ethanol compared to gasoline, which is particularly effective in suppressing end gas knock in direct injection engines [16]. Because ethanol is an oxygenated fuel and has higher laminar flame speed than gasoline, the combustion efficiency and engine-out emissions of total hydrocarbons (THC) and carbon monoxide (CO) can be lower than gasoline. Previous studies have shown that the faster heat release rate and lower flame temperature of ethanol can result in higher engine thermal efficiency due to lower heat loss and higher γ, and also lower NOx emissions due to lower peak combustion temperature compare to gasoline [16–18]. However, ethanol has lower LHV compared to gasoline, which results in higher fuel consumption for producing the same amount of work.

The objective of this study was to conduct experimental testing in order to analyze the effects of fuel properties on the lean misfire limit of SI combustion and assess their effects on engine performance and emissions. The following sections describe the experimental setup and methodology, as well as the results obtained from experimental testing.

2. Experimental setup and methodology

Experiments were performed on a single-cylinder, four-stroke, spark ignited Cooperative Fuel Research (CFR) engine, which has variable compression ratio (6:1–18:1). The engine specifications are shown in Table 1 and the schematic diagram of the experimental setup is shown in Fig. 1. The engine was coupled to an active DC dynamometer for measuring engine speed and torque. The intake air flow rate was measured and controlled with an Alicat MCRW-500SLPM-D/5M mass flow meter mounted upstream of the intake plenum. The liquid fuels were injected into the intake port, but the gaseous fuels were stored in compressed gas tanks and fumigated to the intake plenum to mix with the intake air. A second Alicat MCR-100SLPM-D/5M mass flow meter was used to measure and control the mass flow rate of the gaseous fuels. In-cylinder pressure data was measured using a Kistler 7061B piezoelectric pressure transducer on the cylinder head. A BEI XH25D-SS-1024 crank angle encoder was mounted on the engine shaft for measuring crankshaft position with a resolution of 0.2 crank angle degrees (CAD). For each operating point, engine data for 200 cycles were recorded for and post-processed with in-house, high fidelity, heat release analysis routines. Emissions were measured with a Horiba MEXA-7100DEGR motor exhaust gas analyzer.

Table 1
CFR engine specifications.

Bore (mm)	82.6
Stroke (mm)	114.3
Connecting Rod Length (mm)	254
Displaced Volume (cm^3)	611.7
Clearance Volume (cm^3)	87.4
Compression Ratio	8:1
Fueling Method	Port fuel injection
Engine Speed (rev/min)	1200

The engine was operated at 1200 rev/min, with compression ratio fixed at 8:1 and intake pressure of 75 kPa. Before collecting any data, the engine was conditioned to ensure thermal equilibrium and steady state operation. All operating points shown in this study were collected with spark timing set for Maximum Brake Torque (MBT) at each point. Table 2 below shows the spark timing for each fuel at specific fuel-air equivalence ratio values. For each set of experiments conducted with the four different fuels, the engine was started with the fuel-air ratio set at or close to stoichiometry and then it was progressively decreased until the lean misfire limit was met (COV IMEP > 5%). E10-gasoline was used as the baseline fuel and three different alternative fuels were used during the experiment: (i) 190 proof ethanol (95% ethanol, 5% water vol.), (ii) compressed natural gas (95% CH_4 vol.), and (iii) syngas (60% H_2 and 40% CO% vol.). The relevant fuel properties are listed in Table 3.

3. Results and discussion

3.1. Load and volumetric efficiency

Fig. 2 shows the net indicated mean effective pressure (IMEPn) for the four different fuels as a function of equivalence ratio. As expected, IMEPn decreases with decreasing ϕ due to the lower amount of fuel oxidized and lower heat release. The ϕ ranges for E10-gasoline and ethanol were similar, and combustion with ethanol resulted in comparable IMEPn with gasoline throughout the ϕ sweep. Near stoichiometry, combustion with ethanol resulted in slightly higher IMEPn than gasoline due to the higher in-cylinder pressure for ethanol. This was enabled by the higher laminar flame speed of ethanol and higher octane rating than gasoline, which allowed combustion phasing closer to TDC and more advanced spark timing without knock. However, as the ϕ was reduced, the high latent heat of vaporization of ethanol played an important role and significantly reduced the cylinder temperature, resulting in longer burn duration and lower cylinder pressure than gasoline at lean conditions, thus negatively affecting the work output.

By comparing the two gaseous fuels with gasoline and ethanol, it can be seen that both natural gas and syngas have lower IMEPn than gasoline and ethanol. Natural gas has overall higher IMEPn values than syngas, except for ϕ of 0.63, where the spark advance for natural gas was much higher than syngas, resulting in more heat release late in the compression stroke, which reduced the IMEPn at that point. Natural gas had a ϕ range of 0.63– 0.98. The reduction in IMEPn for natural gas