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Influence of ignition timing on combustion and emissions of a spark-ignition methanol engine with added hydrogen under lean-burn conditions

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ABSTRACT

Ignition timing is an important parameter that impacts flame formation, early combustion process, and emissions of spark-ignition (SI) engines. Hydrogen as an auxiliary fuel may improve combustion and emission characteristics of SI engines. In this study, we experimentally investigated the effects of ignition timing on combustion and emissions of an SI methanol engine with added hydrogen at different engine speeds. At low engine speeds with various ignition timings, increasing hydrogen decreases indicated mean effective pressure, maximum cylinder pressure, maximum heat release rate, and combustion duration. While at high engine speeds with different ignition timings, more hydrogen increases the indicated mean effective pressure, maximum cylinder pressure, maximum heat release rate, and decreases the ignition delay, combustion duration, and COV_{imep}. By comparison with cases without hydrogen, the COV_{imep} can be respectively reduced by 21.5% and 36.8% with hydrogen ratios of 3% and 6% at engine speed of 2400 rpm and ignition timing of 28 °CABTDC. In addition, hydrogen additive decreases the carbon monoxide (CO) and hydrocarbon (HC) emissions at low engine speeds, but increases the nitrogen oxides and soot emissions at high engine speeds under various ignition timings.

1. Introduction

Fossil fuel plays a key role in society. Direct and indirect energy influences the economy, health, transportation and so on. Transportation is mostly dependent on fossil-based liquid fuels, such as gasoline, diesel, and jet fuels. However, the overuse of fossil fuels has a negative impact on air pollution, global warming, and climate change [1]. Methanol is a good fuel candidate for conventional fossil-based fuels [2,3]. A high oxygen content in methanol can reduce smoke and particulate emissions [4,5]. Meanwhile, methanol has a high octane rating and latent heat of vaporization [6,7]. However, the behaviors of the low vapor pressure and high latent heat of vaporization of methanol will lead to cold-start difficulties of SI methanol engines under low temperatures [8].

As an excellent fuel for cars with good combustion and emission behaviors, hydrogen may improve the combustion and emission performance of SI methanol engines [9–11]. Due to fast flame propagation, wide flammability limits, and low minimum ignition energy of hydrogen, it is an ideal fuel additive that enhances lean-burn capabilities [12]. Added hydrogen may extend the lean operation limit of SI engines and achieve a high engine thermal efficiency and low NO_x emissions [13].

Wu et al. [14] compared the combustion behaviors of an SI methanol/gasoline engine at idle conditions, and found that the indicated thermal efficiency increases; the flame development and propagation periods shorten; the coefficient of variation in indicated mean effective pressure decreases, and the emissions of HC, CO and NO_X decrease at every excess air coefficient of SI methanol engines compared with SI gasoline engines. Hedfi et al. [15] have numerically investigated the combustion of a bioethanol engine, and found that delayed ignition results in increased gas mixture temperature and cylinder pressure. Li et al. [16] dealt with the optimal injection and ignition timings of a methanol engine, and found that optimal injection and ignition timings had a significant effect on combustion and exhaust emissions of methanol engines.

Zhang et al. [17] experimentally studied the cold start performance of hydrogen/methanol engines and showed that both flame development and propagation periods reduce with added hydrogen, and found

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that CO and HC emissions decrease, as well as the PM (particulate matter). AçIkgöz et al. [18] investigated the emission characteristics of an SI hydrogen/methane engine. By adding more hydrogen, the brake thermal efficiency increases and then reaches an almost constant value. Huang et al. [19–21] experimentally investigated the effects of natural gas/hydrogen blends in a direct injection SI engine on combustion and emission characteristics. Sarli et al. [22–25] reported the beneficial effect of hydrogen/natural gas in terms of increase in burning velocity and overall flame stability. Gong et al. [26] performed a numerical study on combustion and emission in a DISI (direct-injection spark-ignition) methanol engine with hydrogen addition. The CO decreases and the NO (nitric oxide) increases with increasing hydrogen, whereas formaldehyde and unburned methanol decrease significantly. Ji et al. [27] numerically investigated the combustion process in an SI engine fueled with hydrogen-gasoline blends, and found that the hydrogen addition availed the increases in flame propagation speeds and degree of flame wrinkling. Karagöz et al. [28] studied the effect of hydrogen and oxygen addition as a mixture on emissions and performance of a gasoline engine, and found that brake power and brake thermal efficiency increase by adding hydrogen; HC and CO emissions decrease, whereas the NO_X emissions dramatically increases simultaneously.

Ignition timing is an important parameter that impacts flame formation, early combustion processes and exhaust emission behaviors of SI engines [29]. Shi et al. [30] investigated the effect of spark timing on performance of a hydrogen engine, and found that the brake thermal efficiency first rises and then falls with the advanced spark ignition angle. Postponing the spark timing also causes NO_X, HC and CO emissions to decrease. When the hydrogen volume fraction increases, the NO_X emissions rise and the HC and CO emissions drop. Elsemary et al. [31] investigated high hydrogen percentage addition effects on performance of hydrogen-gasoline engines, and showed that the fuel consumption decreases and thermal engine efficiency increases at ignition timing of 30 °CABTDC. Zhang et al. [32] performed the combustion and emissions analysis of a hydrogen/methanol engine at excess air ratio of 1.20, and found that the indicated thermal efficiency first increases and then decreases with increased spark advance angles. Flame development period prolongs whereas the flame propagation period shortens with the increase of spark advance. HC and CO emissions decrease after adding hydrogen.

Added hydrogen can effectively extend the lean limit of SI engines [33–35]. Zhang et al. [36] studied the performance of a hydrogen/ethanol engine at lean conditions. They found that the highest thermal efficiency improves 6.07% after 3% hydrogen is added and perpared to be mixed with the intake air. Du et al. [37] investigated the effects of hydrogen fractions on lean burn combustion and emission characteristics of SI gasoline engines. Amrouche et al. [38] performed an experimental evaluation of ultra-lean burn capability of a hydrogen/ethanol Wankel engine, and indicated that the ultra-lean operation limit of pure ethanol Wankel engine extends with hydrogen addition to improve engine stability. Similarly, Zhang et al. [39] investigated the lean combustion performance of a hydrogen/n-butanol engine, and affirmed the enhancing effect of hydrogen together with mitigated CO and HC emissions.

The above descriptions provide a detailed review on the combustion and emission effects of hydrogen/gasoline, n-butanol, natural gas, DME, methanol, and ethanol SI engines. Studies of the effects of ignition timing on combustion and emissions with hydrogen addition are mostly carried out under a constant excess air ratio, engine speed, and load condition. In general, most excess air ratios occur between 1.0 and 1.2. However, less attention has been given to combustion and emission characteristics with added hydrogen under lean combustion (excess air ratio ≥ 1.40) for different engine speeds and ignition timings, particularly soot emissions. Therefore, it is necessary to study SI methanol engine performance to guarantee stable combustion for added hydrogen at different ignition timings and engine speeds under lean-burn conditions. In this study, extensive investigation was conducted on the combustion and emission effects of varying ignition timings with hydrogen addition at lean burn and different engine speeds. Under lean-burn conditions with constant excess air ratio of 1.40, the effects of ignition timing and added hydrogen on the combustion and emissions of methanol engines are studied. These results are helpful to develop an ignition-control strategy and to understand the lean combustion characteristics of hydrogen enriched methanol SI engines, in particular the relationship between NO_X and soot at different engine speeds.

Table 1
Engine specifications.

Engine specifications	
Cylinder bore (mm)	79.5
Cylinder stroke (mm)	80.5
Displacement (cm^3)	1598
Compression ratio	10:1
Maximum power/speed (kW/rpm)	85/5800
Maximum torque/speed (Nm/rpm)	160/4000

2. Experimental and procedure

2.1. Experimental setup

An inline, four-cylinder, water-cooled, inlet-port fuel injection and spark-ignition GN16 gasoline engine was used for the test engine. The test engine specifications are shown in Table 1, and the experimental system is shown in Fig. 1.

The test fuels were industrial-grade methanol and hydrogen with a purity above 99.9%. The properties of fuel are shown in Table 2.

An auxiliary combustion of the hydrogen-enriched port injection was used. The methanol and hydrogen fuel injection systems were installed separately and worked independently. The injection nozzles of methanol and hydrogen were mounted on the intake manifold. The methanol injection pressure was 0.4 MPa. Hydrogen injection pressure was 0.2 MPa with a pressure regulator. The hydrogen gas source is the 15 MPa multi-cylinder parallel gas supply system, and the supply pressure is stable at 0.2 MPa after two-stage pressure reduction. The amount of methanol and hydrogen injected per cycle, injection timing of methanol and hydrogen, and ignition timing were controlled by an electronic control unit. A Motohawk general-purpose controller with a Freescale MPC565 main control chip was used to replace the original electronic control unit. An AVL SL102 three-phase asynchronous dynamometer was used to record the instantaneous engine speed and torque. A Kistler 6117BFD17 piezoelectric pressure transducer was used to measure the cylinder pressure. An encoder was used to obtain the crankshaft position which couples the cylinder pressure as a function of crank angle (CA). An AVL INDISET 630 combustion analyzer was used to record and analyze the cylinder pressure. An AVL AMA4000 exhaust gas analyzer was used to record the exhaust emissions. The exhaust soot was measured with an AVL 439 opacimeter and the results were given as an opacity N (number) (%). An ETAS ES631 lambda analyzer was used to measure and record the excess air ratio. A Kistler CDS-DFL3x-5 bar meter was used to measure the methanol consumption. A Beijing Sincerity DWF-1-1-AB meter was used to measure the hydrogen flow rate. An ABB NW80 meter was used to measure the air flow. The detailed parameters, accuracy, type, and manufacturer of the instruments mentioned above are provided in Table 3.

The ignition delay is the CA between the ignition start and the burned start. The burned start is the CA of the burned fuel mass 10%. The burned end is the CA of the burned fuel mass 90%. The combustion duration is the CA from the burned start to the burned end.

COV_{imep} (coefficient of variation in indicated mean effective pressure) is defined as: