Fuel xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Comparative study on alcohol–gasoline and gasoline–alcohol Dual-Fuel Spark Ignition (DFSI) combustion for engine particle number (PN) reduction

Hui Liu [a], Zhi Wang [a,*], Yan Long [a], Shouzhi Xiang [a], Jianxin Wang [a], Mohammad Fatouraie [b]

[a] *State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China*
[b] *Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, United States*

HIGHLIGHTS

- First study to compare the effect of alcohol–gasoline and gasoline–alcohol DFSI on PN reduction.
- With increasing alcohols mass ratio, the PN of all DFSI tests could be reduced by higher than 95%.
- Gasoline–alcohol DFSI shows higher potential in PN reduction than alcohol–gasoline DFSI.

ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form 4 June 2015
Accepted 17 June 2015
Available online xxxx

Keywords:
Alcohols
Gasoline
Dual-Fuel Spark Ignition Combustion
Particle number
Size spectrum

ABSTRACT

This experimental work systematically compares the stoichiometric alcohol–gasoline and gasoline–alcohol Dual-Fuel Spark Ignition (DFSI) combustion for engine particle number (PN) reduction and fuel economy improvement using a high compression ratio gasoline engine. Alcohol–gasoline DFSI is based on port fuel injection (PFI) of alcohols with high oxygenated content, high octane number and high latent heat of vaporization and direct injection (DI) of high energy density and high volatility fuel. Alternatively the gasoline–alcohol DFSI is based on PFI of gasoline and DI of alcohols. Two different alcohols were used, including methanol and ethanol for both DFSI strategies. Alcohol mass ratio was varied from 0% to 100% for all DFSI combustion control strategies. Both alcohol–gasoline DFSI and gasoline–alcohol DFSI are effective approaches of using alternative alcohol fuels in practical gasoline engines with the potential to reduce PN and improve fuel economy. With increasing alcohol mass ratio, significant reductions of the PN were observed for both combustion strategies, which could result in a more than 95% reduction of PN compared to the baseline. The magnitudes of the particle number density for the nucleation and the accumulation peaks decreased dramatically for all DFSI combustion control strategies. Gasoline–alcohol DFSI generally showed higher fuel economy improvement and PN reduction compared to the alcohol–gasoline DFSI.

1. Introduction

Energy savings coupled with reduction in emissions have been pressing global issues of the past few decades. Automotive industry is following the trends by improving the technologies to achieve more efficient and environmentally friendly internal combustion engines (ICEs). For spark ignition (SI) engines, gasoline direct injection (GDI) dominates the developing direction due to the benefits of excellent fuel economy. However, high PM (particulate matter) emissions are associated with GDI engines due to wall wetting effects and sooting propensity inherent to gasoline. To balance the fuel economy and PM trade-off, recent studies have investigated the particle size, composition, number and surface

Abbreviations: AFR, Air/fuel ratio; B, Fuel consumption rate; BSFC, Brake Specific Fuel Consumption; CA, Crank angle; COV, Coefficient of Variation; DI, Direct injection; E–G, Ethanol PFI with gasoline DI; G–G, Gasoline PFI with gasoline DI; GDI, Gasoline direct injection; ICE, Internal combustion engine; MBT, Minimum spark advance for best torque; M–G, Methanol PFI with gasoline DI; P_e, Effective Power Rate; PM, Particulate matter; RON, Research octane number; TDC, Top dead center; W_e, Effective Power; WOT, Wide Open Throttle; ATDC, After top dead center; BMEP, Brake Specific Effective Pressure; $BSFC_{equivalent}$, Equivalent heat value Brake Specific Fuel Consumption; CA50, Crank angle for 50% MFB; DFSI, Dual-Fuel Spark Ignition; D_p, Particle Diameter; G–E, Gasoline PFI with ethanol DI; G–M, Gasoline PFI with methanol DI; GMD, Geometric Mean Diameter; IMEP, Indicated Mean Effective Pressure; MFB, Mass fraction burn; P_i, Indicated Power; PFI, Port fuel injection; PN, Particle number (particulate matter emissions measured by number); SI, Spark ignition; V_s, Cylinder Displacement; W_i, Indicated Power.

* Corresponding author.
E-mail address: wangzhi@tsinghua.edu.cn (Z. Wang).

http://dx.doi.org/10.1016/j.fuel.2015.06.059
0016-2361/© 2015 Published by Elsevier Ltd.

area etc. [1–8]. GDI engine particles have been characterized with two modes, including nucleation (condensed volatile material, mainly sulfate and heavy hydrocarbons) and accumulation (carbonaceous in nature) mode. Optimized piston bowl shape and combustion chamber geometry, advanced fuel injection control strategies, intake flow motion, etc. have been used to reduce particle number (PN) [9–11]. However, to comply with the more and more stringent emissions legislations, huge challenges still exist and significant improvements need to be done. Dual-injection, combining the benefits of both GDI and PFI (port fuel injection), and alternative fuels (for example, alcohols) with oxygenated content could be a potential method to reduce PN and fuel consumption simultaneously.

Alcohols have been proven to be promising alternative fuels for ICE application [12–18]. The chemical and physical properties of methanol and ethanol as well as the gasoline baseline are presented in Table 1. Briefly, the oxygen content in alcohols could enhance complete combustion and decrease PN [19,20]. With high vaporization latent heat, alcohols could reduce mixture temperature, allowing advanced combustion phasing [21]. Also high octane numbers for alcohols allow increased compression ratios to improve the thermal efficiency and the fuel economy.

Many researchers have investigated dual-fuel dual-injection in SI engines using alcohols and gasoline. Representative studies based on turbocharged 'Ecoboost' engines have been reported by Stein et al. [22] and Whitaker et al. [23]. This engine utilizes gasoline PFI and E85 (85% ethanol with 15% gasoline) DI for reducing fuel consumption and suppressing knock. A single cylinder dual-injection engine was developed by Xu et al. [24–26]. They reported that the indicated efficiency increased when using any ethanol fraction in DI and resulted in higher combustion and fuel conversion efficiencies compared to gasoline. The knock-limit could also be extended effectively by dual-fuel dual-injection method. Gasoline PFI with ethanol DI in a boosted engine was used to suppress knock effectively by Cohn and Bromberg [27]. Ethanol and gasoline dual-injection could also be used to increase high volumetric efficiency proposed by Zhuang et al. [28]. A new 3.5 l V6 Toyota dual-fuel dual-injection engine was proposed by Ikoma et al. [29] to improve full load fuel economy and peak torque. For part load, ethanol and gasoline dual-injection could also be used to get high fuel efficiency, which was proposed by Wurms et al. [30]. Ethanol PFI with gasoline DI was used to improve compression ratio from 9.5 to 13.3, which was proposed by Kim et al. [31]. Previous work [32] by the authors investigated the differences between the alcohol–gasoline (alcohols PFI with gasoline DI) and gasoline–alcohol (gasoline PFI with alcohols DI) DFSI with dual-injection for knock suppression.

Table 1
Properties of methanol, ethanol, and gasoline.

Property	Methanol	Ethanol	Gasoline
Chemical formula	CH_3OH	C_2H_5OH	C5–C11
Relative molecular mass	32	46	95–120
Density (kg/L)	0.795	0.79	0.700–0.750
Boiling point (°C)	65	78.4	25–215
Flash point (°C)	12	13	−40
Latent heat of vaporization (kJ/kg)	1103	840	373
Stoichiometric heat of vaporization (kJ/kg_{air})	171.5	93.9	25.8
Stoichiometric air–fuel ratio	6.5	8.95	14.7
Auto-ignition temperature (°C)	500	363	300–400
Lower heating value (MJ/kg)	19.83	26.9	42.9
Lower heating value (MJ/L)	15.7	21.3	31.9
Mixture heating value with $\lambda = 1$ (kJ/m^3)	3557	3593	3750
RON	110	108	97
Laminar flame speed (m/s)	0.523	0.5	0.38

To the best of the authors' knowledge, no research in the literature has systematically compared the effects of stoichiometric alcohol–gasoline and gasoline–alcohol DFSI combustion on PN reduction, which was investigated in this study. Alcohol–gasoline DFSI is based on port fuel injection (PFI) of alcohols with high oxygenated content, high octane number and high latent heat of vaporization and direct injection (DI) of high energy density and high volatility fuel. Alternatively the gasoline–alcohol DFSI is based on PFI of gasoline and direct injection of alcohols.

2. Experimental setup and methodology

2.1. Experimental setup

The schematics of alcohol–gasoline and gasoline–alcohol DFSI with dual-injection for PN reduction are shown in Fig. 1. Two different alcohols including methanol and ethanol were used in this study. Two alcohol–gasoline DFSI combustion control strategies were studied, including M–G (PFI-methanol and DI-gasoline) and E–G (PFI-ethanol and DI-gasoline), while G–M (PFI-gasoline and DI-methanol) and G–E (PFI-gasoline and DI-ethanol) were investigated comparatively. The PFI to DI fuel ratios were adjusted in real-time while the overall air to fuel ratio (AFR) was maintained stoichiometric, to ensure the compatibility with the three-way catalyst to achieve high efficient emission reduction.

The physical and chemical properties of gasoline, methanol and ethanol are listed in Table 1 [24,33] and the specifications of the test engine are listed in Table 2. The schematic of the experimental setup is shown in Fig. 2. Briefly, the charge output from the in-cylinder pressure transducer Kistler model 6052C was converted to an amplified voltage using a Kistler model 5011 charge amplifier. A crank-shaft encoder (AVL 365) with 1440 pulses per engine cycle was used for engine crank angle detection. Combustion analysis and crank angle-based high-speed data acquisition (DAQ) were performed using an AVL IndiMODUL system. The AFR was measured using a NTK air–fuel ratio instrument. An ETAS INCA electronic control system was used to provide flexible DI fuel injection with injection pressure of 150 bar. A PC-hud electronic control system provided by Delphi was used to control port fuel injection. The port injection pressure was kept constant at 6 bar. Two flow meters were used to measure the volume rate of fuel consumption. Engine load (BMEP, Brake Mean Effective Pressure) was recorded by the dynamometer. DMS500 was used to characterize the engine-out particulate matter emission, which is a fast-response particle size and number spectrometer. The device was sampling at the exhaust pipe to measure the particle number concentrations and the particle size distribution characteristics. The measurements range of DMS500 is 5–1000 nm with a data-logging frequency of 10 Hz and a T10–90% response time of 200 ms.

2.2. Experimental methodology

Systematic comparison of the effects of stoichiometric alcohol–gasoline (including M–G and E–G) and gasoline–alcohol (including G–M and G–E) DFSI on engine fuel economy, PN and PN size spectrum was conducted by engine experiments. The engine was a naturally aspirated with high compression ratio of 13:1. In each test, the percentage of alcohols injection was varied from 0% to 100%. The test matrix is summarized in Table 3. Since PM emission increases with the increase of GDI engine load, PN are discussed for M–G and G–M DFSI combustion control strategies at WOT (wide open throttle) condition.

Table 4 shows the engine operation conditions. Initially the baseline condition was established for the study. Gasoline was

Please cite this article in press as: Liu H et al. Comparative study on alcohol–gasoline and gasoline–alcohol Dual-Fuel Spark Ignition (DFSI) combustion for engine particle number (PN) reduction. Fuel (2015), http://dx.doi.org/10.1016/j.fuel.2015.06.059