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Dual-Fuel Spark Ignition (DFSI) combustion fuelled with different alcohols and gasoline for fuel efficiency

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HIGHLIGHTS

- Dual-Fuel Spark Ignition (DFSI) with dual-injection is used to improve fuel economy and suppress knock.
- Alcohols–gasoline DFSI with different alcohols could suppress knock and improve fuel economy effectively.
- M–G DFSI exhibits better anti-knock performance and higher fuel efficiency than other DFSI modes.

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ABSTRACT

This paper investigates an experimental study of Alcohols–gasoline Dual-Fuel Spark Ignition (DFSI) Combustion for knock suppression and high fuel efficiency using a gasoline engine with high compression ratio. Alcohols–gasoline DFSI is organized using a port-fuel-injection (PFI) of high oxygenated, high latent heat and high octane number fuel to suppress knock and a direct injection (DI) of high energy density and high volatility fuel to extend high load. Systematical comparison about the effect of stoichiometric M–G (PFI-Methanol and DI-Gasoline), E–G (PFI-Ethanol and DI-Gasoline), E85W15–G (PFI-15% water and 85% ethanol and DI-Gasoline) and G–G (PFI-Gasoline and DI-Gasoline) DFSI on engine knock suppression was conducted. For each test, the percentage of PFI-Alcohol was varied from 0% to 100%. The effects of these combustion modes on knock-limit extension, fuel economy, and combustion characteristics were investigated. Alcohols–gasoline DFSI is a potential approach of using alternative alcohol fuels in practical gasoline engines with significant improvement in engine efficiency and knock suppression. M–G DFSI exhibits better anti-knock performance and achieves higher fuel efficiency than other combustion modes.

1. Introduction

For gasoline internal combustion engines (ICEs) in automotive industry, gasoline direct injection (DI) combined with turbocharging, which is named as downsized gasoline engine, occupies the mainstream of gasoline ICE development [1] because of its advantages in fuel economy. However, engine knock with high pressure rise and pressure oscillation caused by end-gas auto-ignition is still the big obstacle for deep improvement of fuel consumption. Researchers are seeking new effective methods for knock suppression and subsequent fuel economy improvement. Dual-injection, which consists of DI and port fuel injection (PFI), combined with alternative fuels could be one promising method.

Alcohols are promising alternative fuels for internal combustion engines [2–8]. In this paper, methanol, ethanol and E85W15 (15% water and 85% ethanol, by volume) were investigated. Characteristics of alcohols with high vaporization latent heat, high octane number, high oxygenated content and high laminar flame speed are listed in Table 1 [9–11]. The advantages of these properties concerning knock-limit extension and fuel economy improvement could be referred to Ref. [12]. Furthermore, dual-injection with flexible online Alcohols–gasoline blending combines the advantages of both alcohols and flex-fuel approaches [13].

Abbreviations: AFR, Air Fuel Ratio; AP_{max}, Crank Angle of the Maximum Pressure; B, Fuel consumption rate; BSFC, Brake Specific Fuel Consumption; CA50, Crank angle for 50% MFB; DFSI, Dual-Fuel Spark Ignition; E–G, Ethanol PFI with Gasoline DI; ICE, Internal Combustion Engine; ISFC, Indicated Specific Fuel Consumption; MBT, Minimum Spark Advance for Best Torque; M–G, Methanol PFI with Gasoline DI; P_{max}, maximum pressure; PFI, port fuel injection; SI, Spark Ignition; V_s, Cylinder Displacement; W_i, Indicated Power; ATDC, After Top Dead Center; $APRR_{max}$, Crank Angle of the Maximum Pressure Rise Rate; BMEP, Brake Specific Effective Pressure; $BSFC_{equivalent}$, Equivalent heat value Brake Specific Fuel Consumption; COV, coefficient of variation; DI, direct injection; E85W15–G, 85% ethanol and 15% water PFI with gasoline DI; IMEP, Indicated Mean Effective Pressure; KI, knock Intensity; MFB, Mass Fraction Burn; P_i, Indicated Power; P_e, Effective Power Rate; PRR_{max}, maximum pressure rise rate; TDC, top dead center; W_e, Effective Power.

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Table 1
Properties of methanol, ethanol, and gasoline.

Property	Methanol	Ethanol	Gasoline
Chemical formula	CH_3OH	C_2H_5OH	C_5–C_{11}
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
LCV (MJ/kg)	19.83	26.9	42.9
LCV (MJ/L)	15.7	21.3	31.9
Lower heating value (kJ/kg)	20,260	27,000	44,000
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

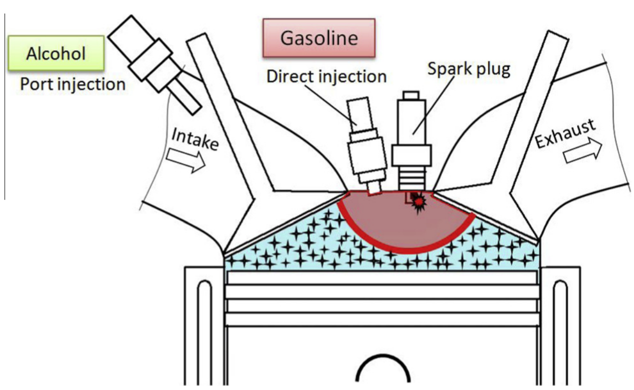

Fig. 1. Schematic of Alcohols–Gasoline Dual-Fuel Spark Ignition Combustion.

Dual-fuel dual-injection spark ignition combustion using alcohols and gasoline in internal combustion engine has been conducted by many researchers. Cohn and Bromberg [14] found that gasoline–ethanol dual-injection boosted engine could suppress knock effectively. Ikoma et al. [15] observed improved performance and fuel economy using dual-injection. Zhu et al. [16] found that gasoline PFI with E85 DI could increase IMEP (Indicated Mean Effective Pressure). Stein and Whitaker [17] developed PFI-Gasoline with DI-E85 dual-injection turbo-charged 'Ecoboost' engine for improving engine efficiency and suppressing knock. Xu et al. [18] researched dual injection on a single cylinder research engine. The results showed that IMEP was improved to 8.5 bar with increasing DI ethanol mass fraction. Wurms et al. [19] achieved higher fuel efficiency at part loads using dual-injection when compared with conventional single injection. Zhuang et al. [20] observed high volumetric efficiency by using ethanol and gasoline dual-injection. Kim et al. [21] investigated gasoline-DI with ethanol-PFI to increase compressing ratio, causing significantly better engine efficiency. Catapano et al. [22] found PFI-Gasoline and GDI-ethanol dual fuel combustion could get low HC and CO emissions. Zhang et al. [23] investigated a detailed oxidation mechanism for the prediction of unregulated emission, such as formaldehyde and so on. The results show that unregulated emissions can also be effectively solved by TWC.

From the above analysis, most studies of dual-fuel dual-injection combustion modes by using alcohols and gasoline in ICE focus on injecting alcohol directly into cylinder rather than into the intake port, which is different with the approaches in this paper. Furthermore, no research compared the effect of different alcohols combined with gasoline on engine knock suppression. This work systematically compares the potentials of Alcohols–gasoline DFSI combustion fuelled with different alcohols and gasoline on knock suppression. The schematics of Alcohols–gasoline DFSI combustion system are shown in Fig. 1 [12]. Three different Alcohols–gasoline combustion modes were studied, including M–G (PFI-Methanol and DI-Gasoline), E–G (PFI-Ethanol and DI-Gasoline) and E85W15–G (PFI-15% water and 85% ethanol and DI-Gasoline) DFSI, while G–G (PFI-Gasoline and DI-Gasoline) DFSI was selected as the reference. The PFI to DI fuel ratios are flexibly controlled on-line. The overall air to fuel ratio (AFR) was maintained stoichiometric, which means the three-way catalyst (TWC) can be applied to achieve high efficient emission reduction to meet the emissions legislations.

2. Experimental setup and methodology

2.1. Experimental setup

The physical and chemical properties of gasoline, methanol and ethanol are listed in Table 1 [13,24]. The specifications of the test engine are listed in Table 2. The schematic of the experimental setup is shown in Fig. 2 [12]. Kistler model 6052C pressure transducer was used to test cylinder pressure, while the charge output from this transducer 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. Combustion analysis and crank angle-based high-speed data acquisition (DAQ) are 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. A PC-hud electronic control system provided by Delphi was used to control port fuel injection. Two flow meters were used to record the fuel consumption by volume rate. Engine load (BMEP) was recorded by dynamometer.

2.2. Experimental methodology

Systematical comparison about the effect of stoichiometric M–G, E–G, E85W15–G and G–G DFSI on engine knock suppression was conducted by experiments. The engine was natural aspirated with high compression ratio of 13:1. In each test, the percentage of alcohols injection was varied from 0% to 100%. Table 3 shows the test matrix.

Table 4 shows the engine operation conditions. The test process was presented as follows. First of all, gasoline was injected direct into cylinder (without PFI-Alcohol) and all operating parameters, including injection and ignition parameters, etc., were taken from the original engine calibration. This test point was marked as the 'baseline'. Secondly, systematical comparison about the effect of stoichiometric M–G, E–G, E85W15–G and G–G DFSI on engine knock suppression was conducted. The engine was set at stoichiometric condition, the ignition timing was adjusted at MBT (Minimum spark advance for Best Torque) point and the percentage of PFI-Alcohol was varied from 0% to 100%.

Table 2
Specifications of the test engine.

Characteristic	Parameter
Type	4-cylinder in-line, natural aspirated, direct injection
Bore × stroke	83.5 mm × 90 mm
Displacement	1.97 L
Compression ratio	13:1
Injector	Bosch 6-hole, high pressure injector
Fuel	RON 97# gasoline/methanol/ethanol

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