Energy 82 (2015) 395–405

Contents lists available at ScienceDirect

Energy

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

Comparative study on alcohols–gasoline and gasoline–alcohols dual-fuel spark ignition (DFSI) combustion for high load extension and high fuel efficiency

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ARTICLE INFO

Article history:
Received 3 August 2014
Received in revised form
26 December 2014
Accepted 16 January 2015
Available online 13 February 2015

Keywords:
Alcohols
Gasoline
Dual-fuel spark ignition (DFSI) combustion
Engine knock

ABSTRACT

This paper presents an experimental study of the alcohols–gasoline and gasoline–alcohols dual-fuel spark ignition (DFSI) combustion for knock suppression and higher engine 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 of vaporization, and high octane alcohol fuel to suppress knock and a direct injection (DI) of high energy density and high volatility fuel to extend engine load, while gasoline–alcohols DFSI is organized by gasoline PFI and alcohol DI. Three different alcohols were studied, including methanol, ethanol, and hydro-ethanol. The engine was naturally aspirated and operated at stoichiometric condition. In each test, the percentage of alcohol injection was varied from 0 to 100%. The effects of these two combustion modes on knock-limit extension, fuel economy, and combustion characteristics were investigated. Both alcohols–gasoline DFSI and gasoline–alcohols DFSI are promising approaches of using alternative alcohol fuels in practical gasoline engines with significant improvement in engine efficiency and knock suppression. Gasoline–alcohols DFSI exhibits better anti-knock performance and achieves higher fuel efficiency than alcohols–gasoline DFSI.

1. Introduction

Compared to the port fuel injection (PFI) gasoline engines, direct injection (DI) combustion has a greater potential in improving fuel economy and is one of the main engine technologies adopted by auto manufacturers. High boost and DI also hold the potential of the enhanced power density [1]. For automotive engines, engine knock, which occurs due to the end-gas auto-ignition and the subsequent high pressure rise and pressure oscillation in the combustion chamber, would damage the engine. Thus, it is still the main obstacle to further increase compression ratio to improve the thermal efficiency of spark ignition (SI) engines. The traditional methods to suppress knock include retarding ignition timing, enriching mixture, and improving the thermal management of the combustion chamber, etc. However, these methods usually deteriorate fuel economy under high loads. Suppressing engine knock has become the main challenge to achieve better engine efficiency in recent decades.

Alcohols are promising alternative fuels for internal combustion engines (ICEs) [2–8]. In this paper, three alcohol fuels were studied including methanol, ethanol and E85 (15% water and 85% ethanol, by volume). The physical and chemical properties of gasoline, methanol and ethanol are listed in Table 1. At stoichiometric condition, methanol–air and ethanol–air mixtures have the similar heating value as the gasoline–air mixture, which will not reduce engine performance when replacing gasoline. The latent heat of vaporization of the methanol and ethanol is 3 and 2.5 times higher than that of gasoline, which reduce the mixture temperature near top dead center (TDC) resulting in less propensity of engine knock [9]. The octane number of methanol and ethanol is much higher than that of gasoline, which allows higher compression ratio to improve fuel economy. Both methanol and ethanol are oxygenated fuels, which promote combustion efficiency and reduce soot emissions [10,11]. The laminar flame speeds of methanol and ethanol are about twice as that of gasoline, which increases combustion speed, resulting in better combustion phasing.

Alcohols [12–15] are widely used as gasoline blending components nowadays. Typically, alcohols are blended with gasoline in the gas stations, which precludes the possibility of changing

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http://dx.doi.org/10.1016/j.energy.2015.01.049
0360-5442/

Definitions/abbreviations

AFR	air–fuel ratio
ATDC	after top dead center
B	fuel consumption rate
BMEP	brake specific effective pressure
BSFC	brake specific fuel consumption
BSFC$_{\text{equivalent}}$	equivalent heat value brake specific fuel consumption
CA	crank angle
CA50	crank angle for 50% MFB
CA_P$_{\text{max}}$	crank angle of the maximum pressure
CA_PRR$_{\text{max}}$	crank angle of the maximum pressure rise rate
COV	coefficient of variation
DFSI	dual-fuel spark ignition
DI	direct injection
E–G	ethanol PFI with gasoline DI
E85–G	85% ethanol and 15% water PFI with gasoline DI
G–E	gasoline PFI with ethanol DI
G–E85	gasoline PFI with 85% ethanol and 15% water DI
G–M	gasoline PFI with methanol DI
ICE	internal combustion engine
IMEP	indicated mean effective pressure
ISFC	indicated specific fuel consumption
KI	knock intensity
MBT	minimum spark advance for best torque
MFB	mass fraction burn
M–G	methanol PFI with gasoline DI
P_{i}	indicated power
P_{max}	maximum pressure
P_{e}	effective power rate
PFI	port fuel injection
PRR$_{\text{max}}$	maximum pressure rise rate
SI	spark ignition
TDC	top dead center
V_{s}	cylinder displacement
W_{e}	effective power
W_{i}	indicated power

blending ratio on the fly. A better way of using alcohols is via dual-fuel dual-injection, which combines PFI and DI to provide flexible online alcohols–gasoline blending. By leveraging both injection systems simultaneously, different blending ratios can be applied at different engine loads. Dual-injection combines the advantages of both alcohols and flex-fuel approaches [16]. Hence, dual-fuel dual-injection could be one of the key techniques to better use of alcohols in ICEs in the future.

Many studies have been conducted on dual-fuel dual-injection combustion mode using alcohols and gasoline in ICEs. Cohn and Bromberg [17] examined the potential of ethanol (hydrous and anhydrous) boosted direct- and dual-injection engines, to cool the charge and suppress knock. The results of experiment and simulation indicated that gasoline–ethanol dual-injection could effectively suppress knock. Ikoma et al. [18] observed improved fuel economy and torque at full load using a 3.5 L V6 gasoline engine with dual-injection. Zhu et al. [19,20] investigated the combustion characteristics of dual-injection in a single cylinder engine. The results showed that the indicated mean effective pressure (IMEP) decreases with increasing DI fueling, except for some instances of gasoline PFI and E85 DI. Mustafi et al. [21] studied the emissions of a dual fuel engine operating with alternative gaseous fuels. Stein and Whitaker [22,23] developed the dual-injection technology on their ‘Ecoboost’ gasoline turbo-charged direct-injection engines, which used PFI-gasoline with DI-E85 to improve engine efficiency and to avoid knock at low-speed high load conditions. The new research engine ‘Bobcat’ with high compression ratio with dual-injection achieved improved engine efficiency. Wu et al. [24–26] conducted dual injection research 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. [27] developed dual-injection technique in a turbocharged 1.8 L gasoline engine, which achieved higher fuel efficiencies at part loads compared to conventional single injection. Zhuang et al. [28,29] observed higher volumetric efficiency by using ethanol and gasoline dual-injection. However, CO and total hydrocarbon (THC) emissions increased when the amount of ethanol was higher than 36.3% of the total fuel energy used. The knock tendency decreased when ethanol was injected after intake valve closing. NO$_x$ and THC emissions did not change significantly, but CO emissions increased due to the poor mixture uniformity. Kim et al. [30] investigated the efficiency and emission characteristics of dual fuel combustion using gasoline DI and ethanol port injection in an SI engine. Compared to the GDI engine, the compression ratio of dual-fuel engine was increased from 9.5 to 13.3 and achieved significantly better engine efficiency. Catapano et al. [31] studied the effect of PFI-gasoline and GDI-ethanol dual fuel combustion on the performance and exhaust emissions of a small SI engine. Lower HC and CO emissions were observed for dual fuel modes.

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$_{\text{air}}$)	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 (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

From the above analysis, most studies of dual-fuel dual-injection combustion modes focus on DI of alcohol into the cylinder rather than into the intake port. Few studies reported dual-fuel spark ignition (DFSI) [32] by injecting high oxygen content and high octane fuel into the intake port to suppress knock and injecting high energy density and high volatility fuel into the cylinder to extend load to achieve fast transient response. Furthermore, no study compared the differences of alcohols–gasoline (alcohol PFI with gasoline DI) and gasoline–alcohols (gasoline PFI with alcohol DI) DFSI. This work systematically compares the potentials of DFSI combustion fueled with alcohols and gasoline on