Fuel xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Fuel

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

Effects of direct injection timing of ethanol fuel on engine knock and lean burn in a port injection gasoline engine

Q1 Yuan Zhuang, Guang Hong *

Q2 *School of Electrical, Mechanical and Mechatronic Systems, Faculty of Engineering and Information Technology, University of Technology, Sydney, Australia*

HIGHLIGHTS

- Ethanol direct injection + gasoline port injection was experimentally investigated.
- Late ethanol direct injection (LEDI) was effective on suppressing engine knock.
- Early ethanol direct injection (EEDI) resulted in higher efficiency than LEDI did.
- EEDI was more effective on extending the lean burn limit than LEDI was.

ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form 6 June 2014
Accepted 10 June 2014
Available online xxxx

Keywords:
EDI + GPI
Ethanol direct injection
Q3 Gasoline port injection
Fuel injection timing
Engine knock
Lean burn

ABSTRACT

Ethanol is a promising alternative fuel for internal combustion engines due to its renewable feature. To make the use of ethanol fuel more effective and efficient, ethanol direct injection plus gasoline port injection (EDI + GPI) has been investigated in recent years. By directly injecting ethanol into the engine, the advantages of ethanol fuel such as high latent heat of vaporization, fast laminar flame speed, wide flammability and better low temperature combustion stability can be well utilized to enhance engine anti-knock ability and improve lean burn performance. For an engine equipped with direct injection (DI) system, start of injection (SOI) timing is an important control parameter which directly affects the engine performance. This paper reports the investigation to the effect of ethanol fuel SOI timing on knock mitigation and lean burn. Experiments were conducted on a 250 cc single cylinder spark ignition (SI) engine equipped with EDI + GPI system. Ethanol fuel SOI timing before and after the inlet valve closing, defined as early and late injection timings (EEDI and LEDI) were investigated in engine conditions at knock limited spark advance (KLSA) and lean burn limit. The experimental results showed that LEDI was effective on suppressing engine knock and permitting more advanced spark timing. EEDI was less effective than LEDI on mitigating knock due to the increased heat transfer from cylinder wall to gases. The mixture quality may be deteriorated in LEDI conditions which resulted in low engine efficiency and high emissions. Volumetric efficiency was increased and combustion duration was reduced in EEDI conditions. The combined effects of improved volumetric efficiency, reduced combustion duration and moderately advanced spark timing resulted in increased engine thermal efficiency in EEDI conditions. In lean burn, EEDI was more effective on extending lean burn limit. The maximum lambda achieved in EEDI condition was 1.29 when ethanol energy ratio (EER) was 24% and SOI timing was 290 CAD BTDC. LEDI only slightly increased lean burn limit which was just over stoichiometric air–fuel ratio (AFR). In EEDI conditions, IMEP was greater and combustion stability (COV) was better than that in LEDI conditions. The emissions in EEDI conditions were also lower than that in LEDI conditions.

Abbreviations: ATDC, after top dead center; BTDC, before top dead center; COV, covariance of variation; DI, direct fuel injection; EDI, ethanol fuel direct injection; EEDI, early ethanol direct injection; ERR, ethanol/gasoline energy ratio; ECU, electronic control unit; ISHC, indicated specific hydrocarbon; ISNO, indicated specific nitric oxide; IMEP, indicated mean effective pressure; GPI, gasoline port injection; KLSA, knock limited spark advance; LHV, low heat value; LEDI, late ethanol direct injection; SOI, start of injection; HE, heating energy; HC, hydrocarbon; MBT, maximum brake torque; NO, nitric oxygen; PFI, port fuel injection; Lambda (λ), air/fuel equivalence ratio.

* Corresponding author. Address: PO Box 123, NSW 2007, Australia. Tel.: +61 02 95142678.
E-mail addresses: Yuan.Zhuang-1@student.uts.edu.au (Y. Zhuang), guang.hong@uts.edu.au (G. Hong).

http://dx.doi.org/10.1016/j.fuel.2014.06.028
0016-2361/

1. Introduction

Improving engine efficiency and reducing its emissions are the major tasks of recent development in internal combustion technology [1]. This is driven by the society concerns about the global warming and the depletion in supply of fossil fuels. One of the feasible short-to-midterm solutions for addressing the concerns is to use renewable fuels such as ethanol. Many countries and areas have enacted legislations [2] or incentive policies to promote the use of ethanol and other bio/renewable fuels [3,4]. The use of ethanol and other bio/renewable fuels has brought new challenges to automotive sector to develop new technologies. Ethanol direct injection plus gasoline port injection (EDI + GPI) is one of the new technologies in recent development.

Previous studies on SI engines found that using ethanol fuel could help to reduce unburned emissions such as carbon monoxide (CO) and hydrocarbon (HC) [5–7], enhance engine anti-knock ability [8,9], and improve lean burn performance [10,11]. In the current applications, ethanol is externally blended with gasoline at a specific ratio. The applications of this method decreased pollutant emissions and increased engine efficiency in certain engine conditions [12,13]. However, the vehicles may face problems of reduced vehicle coverage, difficult cold start [14], corrosion and reduced lubrication [15]. Moreover, due to the fixed ethanol/gasoline ratio, the ethanol's potential in reducing engine emissions and improving thermal efficiency cannot be fully exploited. Research has already shown that the optimal ethanol/gasoline ratio for maximizing engine efficiency and minimizing emissions was varied with the engine operation condition [6,7]. EDI + GPI dual-fuel injection, on the other hand, provides an opportunity to solve the problems and meet the requirements. It offers greater flexibility of using ethanol fuel because the ethanol and gasoline mixing ratio can be instantly altered according to the engine operation condition and fuel availability. Through adjusting GPI and EDI, the advantages of GPI in forming homogeneous air–gasoline mixture and of EDI in charge cooling can be integrated. The engine performance can therefore be improved.

In SI engines, spark timing is usually selected at its minimum advance for the maximum brake torque (MBT). However, this MBT spark timing is often prevented by the onset of knock. Thus, SI engine's efficiency is limited by the engine knocking. The knocking tendency is related to fuel properties, compression ratio, injection strategies (in direct injection spark ignition (DISI) engines) and engine operating conditions such as spark timing and turbo-charging. In an EDI + GPI engine, its anti-knock ability is strengthened by both the charge cooling enhanced by ethanol's great latent heat and ethanol's high octane number. Stein et al. [16] and Daniel et al. [17] evaluated the effect of ethanol direct injection on knock mitigation in dual-injection engines. In their study, the ethanol fuel SOI timing was fixed before the inlet valve closing. They found that by directly injecting ethanol, the engine knock was substantially suppressed and the engine thermal efficiency was increased when compared with GPI only condition. Although, the effect of dual-injection on knock suppressing has been studied by several pioneer researchers, the relation between SOI timing and knock mitigation has not been investigated yet. The numerical simulation results of Cohen et al. [18,19] indicated that the ethanol fuel SOI timing could significantly affect the dual-injection engine anti-knock ability. It was predicted that if the ethanol was injected before the inlet valve closing, the boost pressure up to 2.4 Bar could be applied without knocking. If the ethanol was injected after the inlet valve closing, greater boost pressure could even be allowed. Moreover, SOI timing also affects mixture homogeneous quality and ultimately the engine efficiency and emissions. Thus, finding the relation between SOI timing and engine knock, efficiency and emissions is necessary in EDI + GPI engine development.

With the rapid development of engine control techniques, lean or stratified combustion has become more applicable to modern DISI engines. In this combustion mode, the greater throttle opening reduces the pumping losses associated with stoichiometric conditions at partial engine load. Lean burn can also reduce (nitrogen oxides) NO_x emissions which are temperature dependent, and HC emissions which are related to the availability of oxygen [20,21]. However, when the mixture is leaned, the combustion may become unstable. It requires precise control of engine parameters such as SOI timing and spark timing, where small variation in these parameters can lead to misfire or in-completed combustion [20]. In EDI + GPI engine, DI may help to form ignitable mixture in adjacent to the spark plug. The use of ethanol may enhance lean burn stability and reduce the time for fuel droplets to evaporate due to its high laminar flame speed and low molecular weight properties. The effect of ethanol on engine lean burn has been studied in port fuel injection (PFI) engine. It was reported that by using ethanol, the engine lean burn limit (maximum achievable lambda, denoted as λ) was increased by a value of 0.2 and the coefficient of variation (COV) of IMEP was reduced by about 2% [22,23]. As a new technology, the study on lean burn in dual-injection engine has not been reported so far and therefore requires investigation.

In a DI engine, SOI timing directly affects the heat transfer and mixture temperature. Earlier fuel injection cools the gas at an earlier time, which results in improved volumetric efficiency but also increases the heat transfer from the wall to the gases. Thus, the overall cooling effect on the charge is compromised. For late injection, the cooling effect due to fuel evaporation can be well preserved, leading to a lower knocking tendency. However, the mixture quality may be reduced and the combustion may be deteriorated due to less time for forming homogeneous mixture [24,25]. The volatility of ethanol is higher than that of gasoline when the temperature is over 410 K due to its single component [20]. This may help to produce more homogeneous mixture and reduce the time for fuel evaporation in DISI engine. Therefore, the SOI timing for ethanol fuel can be retarded to enhance anti-knock ability while maintaining the high quality of the mixture [26,27].

As reviewed above, in the development of ED + GPI engine, investigation to the effect of SOI timing on knock mitigation and lean burn is required. This study was aimed to meet the requirement. Experimental work was carried out on a self-developed EDI + GPI engine. The results presented and discussed include effects of ethanol fuel SOI timing on KLSA, lean burn limit, combustion and emissions.

2. Experimental apparatus

2.1. Test engine and instrumentation

Fig. 1 is a schematic diagram of the test rig. The engine was modified from a Yamaha product YBR250. It is a 4-stroke, air cooled single cylinder motorcycle SI engine with a displacement of 250 cc which represents the cylinder capacity of a light duty passenger car. Table 1 lists the engine's main specifications. The engine was originally equipped with an electronic PFI system operated at a constant fuel pressure of 2.5 Bar and an onboard electronic control unit (ECU). It was modified by adding an ethanol fuel direct injection system and a new ECU which replaced the original one and provided the flexibility of manual adjustment of spark timing, lambda (λ) value, ethanol injection timing and other parameters relevant to the engine operation. The ethanol fuel direct injection system consisted of a six hole injector which has a 34° spray cone angle and a 17° bent axis and a returnless high pressure pump providing fuel pressure in a range of 30–130 Bar.