Fuel 210 (2017) 187–197

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

# The effect of ethanol direct injection on knock mitigation in a gasoline port injection engine

Yuan Zhuang[a], Yejian Qian[a,*], Guang Hong[b]

[a] School of Automotive and Transportation Engineering, Hefei University of Technology, No.93 Tunxi Road, Hefei, China
[b] School of Electrical, Mechanical and Mechatronic Systems, Faculty of Engineering and Information Technology, University of Technology, Sydney, PO Box 123, NSW 2007, Australia

ARTICLE INFO

*Keywords:*
Knock
Ethanol
Direct injection
Gasoline

ABSTRACT

In the development of downsizing and high efficiency spark ignition (SI) engine, overcoming the knock is crucial. One method to suppress knock is to use with high octane number fuels as additives. However, in the current pre-blended fuel such as E10, the blending ratio cannot be varied with the engine operation conditions. The novel ethanol direct injection plus gasoline port injection (EDI + GPI) provides the opportunity to solve the fuel blending problem. Most importantly, EDI + GPI has great potential in anti-knocking. By directly injecting ethanol into the combustion chamber, blending ratio can be adjusted according to the engine conditions and the engine's anti-knocking ability will be strengthened by not only the ethanol's high octane rating but also its great latent heat. In the work, the effect of EDI on suppressing the knock caused by advancing spark timing and increasing inlet air pressure were experimentally investigated on a 250 cc single cylinder motorcycle engine equipped with an EDI + GPI system. Experimental results showed that compared with GPI and gasoline direct injection (GDI), EDI + GPI effectively mitigated engine knock and permitted more advanced spark timing. In the ethanol energy ratio (EER) range from 15% to 35%, every 2% or 3% increment of EER permitted about 2 CAD advance of knock limited spark advance (KLSA). EDI + GPI also showed benefits to combustion, indicated thermal efficiency and emissions (HC and CO) due to the advanced spark timing and ethanol's oxygen content and fast laminar flame speed. In conditions simulating turbocharging, compressed air was used to increase the inlet air pressure from 1.0 to 1.4 atmospheric pressure with the EER increased to handle the raised knock tendency. Indicated thermal efficiency was increased with the increase of inlet air pressure. Exhaust gas emissions in terms of ISCO, ISNO and ISHC increased with the increased inlet pressure and major combustion duration decreased with the increase of inlet pressure. Overall, the results demonstrated the potential of EDI + GPI in anti-knocking and consequently increasing the thermal efficiency in small engines.

## 1. Introduction

Energy security and globe warming are the two major issues the automotive industry is facing to. Based on current trend, the world's petroleum is expected to be depleted in the next 40 years and the globe temperature will be increased about 2 degrees by 2050 due to the use of these carbon based energy [1,2]. Therefore, there is an urgent need to improve IC engines' fuel efficiency, decrease energy consumption and reduce the pollutant emissions in order to address the above issues. Using alternative fuels and synergy these fuels with modern technologies, such as direct injection (DI), turbo-charge and dual-injection, have been regarded as one of the best ways.

Spark-ignition (SI) engine knock is a well-known abnormal combustion phenomenon that constrains engine performance and efficiency [3]. In a SI engine, when the mixture is ignited by spark, the combustion occurs and the flame front subsequently propagates outwards and consumes the unburned mixture on the outside of the flame (called "end gas"), releasing heat and increasing mixture (burned and unburned) pressure. As the end gas pressure and temperature rise to certain degrees due to the compression caused by this process, auto-ignition of the fuel may occur in certain spots [4]. This auto-ignition causes an extremely rapid release of much of the chemical energy stored in the unburned mixture, resulting in large pressure oscillation in the cylinder. In turn, these oscillations produce metallic sound and, if severe enough, can cause major damage to engine components. Due to its potential harm to engines, knock is a fundamental limiting factor in engine design. Certain engine parameters such as spark timing, compression ratios and boost pressures have to be adjusted or limited to

* Corresponding author.
*E-mail addresses:* zhuangyuan@hfut.edu.cn (Y. Zhuang), xjwei@ustc.edu.cn (Y. Qian), guang.hong@uts.edu.au (G. Hong).

http://dx.doi.org/10.1016/j.fuel.2017.08.060
Received 17 April 2017; Received in revised form 17 June 2017; Accepted 15 August 2017
Available online 31 August 2017
0016-2361/

**Nomenclature**

| | |
|---|---|
| ATDC | after top dead center |
| BTDC | before top dead center |
| CO | carbon monoxide |
| DI | direct fuel injection |
| EDI | ethanol fuel direct injection |
| ISCO | indicated specific carbon monoxide |
| ISHC | indicated specific hydrocarbon |
| ISNO | indicated specific nitric oxide |
| IMEP | indicated mean effective pressure |
| PFI | port fuel injection |
| KLSA | knock limited spark advance |
| SOI | start of injection |
| HE | heating energy |
| HC | hydrocarbon |
| MBT | maximum brake torque |
| $NO_X$ | nitric oxygen |
| Lambda | air/fuel equivalence ratio |

avoid knock. However, optimizing these parameters are critical to improve SI engine efficiency. Therefore knock constraints limit the potentially further increase of engine efficiency [5].

Direct injecting technology has been widely adopted in production engines due to its benefits in part-load fuel consumption and full-load torque output [6,7]. One of the significant advantages of DI over conventional port fuel injection (PFI) engine is that the heat of vaporization of the fuel can be extracted from the charge and cools it. This charge cooling effect can be used to increase volumetric efficiency and power output and more importantly, to increase engine efficiency by extending knock limits. Improved knock limits allow the SI engine to adopt higher compression ratios, boost pressures and optimal spark timing [8]. Nevertheless, due to the low latent heat of vaporization of gasoline, the charge cooling effect of DI gasoline is not as significant as that of some alternative fuels with high latent heat of vaporization, such as ethanol. The comparison of different fuels' charge cooling effect has shown that DI gasoline could result in about 10 K charge temperature reduction which was equivalent to 5 units increment in effective octane number. When direct injecting ethanol, the latent heat of vaporization is about 3 times that of gasoline, the decrease of charge temperature reached 50 K and the effective octane number was increased about 18 units [9]. Similarly, the investigation to knock limited compression ratio of ethanol/gasoline blends showed that in full-load condition, the maximum knock limit compression ratio for direct injecting regular gasoline was 9.2. This ratio could be raised to 12.78 when direct injected E85 (85% of ethanol/gasoline blend) [10].

In order to fully exploit the potential of charge cooling in improving knock onset limits and engine efficiency, the ethanol direct injection plus gasoline port injection (EDI + GPI) has recently been in development. In this method, the ethanol fuel is directly introduced into the cylinder chamber through a fuel delivery system separated from that for the gasoline fuel. Thus ethanol's high latent heat of vaporization can be fully utilized and different ethanol/gasoline blending ratios can be supplied to the engine to best suit different working conditions. Cohn et al. conducted numerical simulations on a dual-injection engine. They predicted that if DI ethanol before the inlet valve is closed, the manifold boost pressure up to 2.4 Bar could be potentially achieved. If only PFI gasoline, the maximum achievable boost pressure was less than 0.5 Bar [11,12].

Daniel et al. investigated the effect of ethanol and methanol fuels on knock mitigation in a dual-injection single cylinder engine. In their tests, dual-injection method has demonstrated greater potential in suppressing engine knock over PFI and GDI. The experiments also indicated that DI ethanol/methanol coupled with GPI could lead to the reduction of hydrocarbon (HC) and carbon oxidize (CO) emissions [13].

Stein et al. assessed dual-injection on a 3.5 L gasoline turbocharged direct injection (GTDI) engine with direct fuel injection of E85 and port fuel injection of gasoline [14]. The original compression ratio of the engine was increased from 9.8:1 to 12:1. During the test, the DI E85 fuel was fixed at the amount that was needed to mitigating knock. Their experimental results showed that engine thermal efficiency was largely improved by using DI E85. Gasoline usage was substantially conserved because DI E85 leveraged gasoline fuel efficiency.

Recently, the dual-injection strategy is introduced to realize octane-on-demand concept as it provides flexibility in actively dynamic control of the engine knock (octane rating). In this concept, the engine normally uses a low octane rating gasoline as a main fuel to feed to low and middle load engine conditions, while using another high octane rating fuel, e.g. methanol, ethanol or even water, as knock suppressor in higher engine loads where knock mitigation are needed.

Partridge et al. investigated the octane-on-demand concept in a Toyota D-4(S) 1AZ-FSE 2 L engine [15]. It was found that the less expensive regular grade gasoline could be used more effectively than DI only. Morganti et al. quantified the minimum amount of methanol that must be added to lower octane fuel in order to reproduce the baseline engine performance attained by a market gasoline (RON 95) [16]. Bromberg et al. further developed the octane-on-demand concept in dual-injection engines [17]. Their work evaluated the correlation between octane demand (by DI ethanol) and auto-ignition in different engine configurations and operation conditions. Relations between octane boost requirements (DI ethanol) and different engine displacements, injection strategies, speeds and loads were proposed.

Most investigation to dual-injection has focused on finding the minimum amount of lower alcohol to suppress knock or using certain quantity of octane booster to reproduce high engine load performance which previously can be achieved only by higher octane rating gasoline. The correlation between alcohol or octane booster volumetric percentage/mass fraction and engine load in specific engine configuration has been studied by many scholars. However, relations between DI certain quantity of ethanol and corresponding spark timing advancement and inlet pressure increment were not specified yet. With the development of dual-injection technology and the forthcoming applications, this information is important to engine control and management. Furthermore, previous studies investigated the effect of dual-injection on knock mitigation and octane-on-demand concept normally at knock limited spark advance (KLSA) or maximum break torque (MBT) spark timing. Nevertheless, the study on dual-injection engine performance when spark timing is advanced over MBT spark timing is seldom reported. When engine is at around MBT spark timing, the minimal advance of spark timing may lead to marginally change of engine load output, but significant change of $NO_X$ emissions. Therefore, the knowledge of dual-injection engine performance when spark timing is advance over MBT spark timing is crucial for emission control.

This study is aimed to address the above issues. The experiments were conducted at different engine loads and inlet pressures in order to find out their relations with EDI fraction. The results presented and discussed include the effects of EDI on engine knock caused by spark advance and inlet air pressure increment. Corresponding combustion results and emissions performance are also presented.

## 2. Experimental apparatus

### *2.1. Test engine*

The experiments were performed on a self-developed EDI + GPI research engine system. The engine used is a Yamaha production of