Fuel 215 (2018) 352–362

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Influence of fuel properties on multi-cylinder PPC operation over a wide range of EGR and operating conditions

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ARTICLE INFO

Keywords:
Physicochemical properties
Partially premixed combustion
Engine performance
NOx emissions
Soot reduction

ABSTRACT

To determine the influence of physicochemical properties of fuels on emissions and operating range capacity in partially premixed combustion (PPC), *n*-heptane, gasoline, and *n*-butanol are blended into diesel by volume ratio of 80%, referred to as DH80, DG80, and DB80. Diesel is used as base fuel. Results show that the low viscosity of DH80 and DG80 has an adverse effect on their injection pressure capability and brake specific fuel consumption (BSFC). There is little difference in combustion characteristics between DH80 and diesel even with the great difference in volatility. DH80 achieves extremely high soot reductions compared to diesel at low load, while its reduction effect decreases gradually as load increases. Cetane number (CN) is the key factor influencing the mixing process for the part load, while the ignition delay of low CN fuels is sensitive to speed and load variations. As load increases, the effect of CN on the combustion process is greatly suppressed, and the molecular dilution effect on soot reduction outweighs the effect of CN. DB80 presents the best soot reduction performance due to its multi-dimensional fuel properties, but its full molecular structure potential on soot reduction at high load is limited due to its low energy density.

1. Introduction

The advancement of diesel engine technologies is primarily driven by the emission regulations which motivate engine producers to apply new technologies such as EGR-diluted combustion and advanced after-treatment concepts [1,2]. Currently, the legal levels of NOx emission in Euro 6 and EPA 2010 legislations are 0.4 g/kW-h and 0.27 g/kW-h [3]. Both in the European and US markets, EGR and selective catalytic reduction (SCR) system have been widely used. In achieving near-zero NOx levels, the engine-out NOx emission calibration plays an important role in joint optimization between combustion system and post-processing device [4]. Studies show that the average engine-out NOx emission of EGR-diluted Euro 6 heavy-duty (HD) engines is 4.3 g/kW-h [5]. The California Air Resources Board still claims that a HD Low NOx Program is under research aiming at reducing HD NOx emission limit by 90% to 0.020 g/bhp-hr (0.027 g/kW-h) [6,7]. That means, if the SCR conversion efficiency varies from 99.7% to 97.0% [8], the engine-out NOx should be calibrated from 9.0 g/kW-h to 0.9 g/kW-h. Therefore, it is necessary to discuss the engine suitability for wide NOx targets, and how to prevent the emission deterioration in low engine-out NOx levels in achieving efficient combustion.

In recent years, some novel combustion concepts, such as homogeneous charge compression ignition (HCCI) and low temperature combustion (LTC) have been proposed [9]. And a great deal of progress has been made when fuel property is deliberately considered and designed [10,11]. For EGR-diluted LTC, many studies recognize that blending gasoline into diesel can significantly reduce soot emission without penalty of fuel consumption due to the increase of premixed combustion proportion in LTC mode [12,13]. HCCI also achieves breakthroughs when gasoline fuel was injected in a diesel engine. Then new combustion concepts, such as gasoline PPC [14,15], gasoline direct injection compression ignition (GDCI) [16,17], and low temperature gasoline combustion (LTGC) [18], are introduced. Their applicable engine loads are significantly extended, and the emissions can be roughly controlled within the limit of US 2010 [19–21]. However, their EGR requirement of high load operation ranges from 40% to 60% [18,22]. The pumping losses of PPC mode are considered to be three times higher than conventional diesel combustion and decrease brake

Abbreviations: PPC, partially premixed combustion; BSFC, brake specific fuel consumption; DPF, diesel particulate filter; CN, cetane number; EPA, environmental protection agency; EGR, exhaust gas recirculation; SCR, selective catalytic reduction; HD, heavy duty; HCCI, homogeneous charge compression ignition; LTC, low temperature combustion; GDCI, gasoline direct injection compression ignition; LTGC, low temperature gasoline combustion; BTE, brake thermal efficiency; ITE_{gross}, gross indicated thermal efficiency; CO_2, carbon dioxide; FSN, filter smoke number; LHV, low heating value; GC–MS, gas chromatography–mass spectrometer; VGT, variable geometer turbocharger; BMEP, brake mean effective pressure; CA50, the crank angle at which 50% completion of heat release; SOI, start of injection

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https://doi.org/10.1016/j.fuel.2017.08.099
Received 6 May 2017; Received in revised form 28 June 2017; Accepted 29 August 2017

thermal efficiency (BTE) at EGR rate above 40% down to a level of traditional diesel engine with engine-out NOx calibrated to 2.7 g/kW-h [23,24]. Furthermore, as to the California HD low-NOx regulation limit of 0.027 g/kW-h, a DeNOx after-treatment system seems to be unavoidable, and a reasonable EGR rate should be reconsidered. Therefore, it is necessary to gain an improved understanding of the effect of fuel property combined with engine-out NOx levels from the perspective of emission control under state-of-art air system.

According to the previous studies of our group on EGR-diluted LTC, the soot emissions are effectively reduced due to the changes of fuel properties by blending diesel with low CN fuels such as gasoline and *n*-butanol [25–27]. In fact, when blending ratio changes, fuel physicochemical properties, such as the volatility, viscosity and CN, and the fuel components, such as the aromatics, cycloalkanes, alkanes and oxygen content, can be changed greatly, which probably have a significant effect on the soot emissions. Kalghatgi et al. hold the opinion that the resistance to auto-ignition of a fuel is far more important than its volatility and fuel components [28–30]. Fuels with wide boiling range require less processing in the refinery than today's gasoline or diesel fuels, and their combustion efficiency and stability at part load can be improved due to the increased potential in stratification. While Ojeda et al. [31] claim that good volatility is necessary because it promotes the evaporation of the injected fuel spray and accelerates the fuel/air mixing process, so soot reduction can be observed in tests of lower T90 fuels at similar CN and aromatic content. What's more, the molecular structure is also an important contributor in substantial soot reduction rather than mixing even with up-to-date common-rail injection systems [20]. Tree et al. [32] recognize that all soot emission will be removed if the oxygen content of fuel reached 27–35% by mass. In recent years, *n*-butanol is thought to be an important future fuel biocomponent with excellent properties, such as high oxygen content of 21 wt% and relatively high heat of vaporization which is beneficial for lowering the combustion temperatures. Butanol addition to diesel and biodiesel fuels can increase thermal efficiency and lower unburned emissions and can be considered as a good solution for reducing density, viscosity and thus sustainable usability of biodiesel [33]. Chen et al. [34] and Wang et al. [35] report that, for *n*-butanol/diesel blends, the low CN characteristic and high fuel oxygen are the main contributors in reducing soot emissions. Other properties are small enough to be ignored. Liu et al. [36] also report the relative importance of each fuel property of *n*-butanol/diesel blends on soot reduction. Nevertheless, further studies with high blending ratios under different operating conditions are still needed to reveal the effect of each fuel property on soot reduction. Gasoline and *n*-butanol are selected as the low CN fuels in this study.

Many studies of fuel properties take place on single-cylinder research engine where intake pressure and fuel pressure always come from external air sources and stand-alone fuel circuits for maximum flexibility. However, results from single-cylinder research engine cannot directly represent the real performance of a multi-cylinder version, such as pumping losses and equivalence ratio when using a real air system, and accessory power consumption [37]. For instance, lubricity additive is usually used with low viscosity fuels to prevent failure of common-rail injection systems. But increased parasitic losses could not be completely avoided, which may impose a negative effect on brake fuel consumption [24,37,38]. Furthermore, many gasoline PPC studies mainly focus on low speed operation points where a long ignition duration is relatively easy to reach. Therefore, it is necessary to study the effect of fuel property on engine performance and emissions on a multi-cylinder engine over a wide range of operation conditions. In this paper, the combustion phasing is fixed for different fuels at each load. The engine-out NOx is varied from without EGR to 0.4 g/kW-h. *n*-Heptane, gasoline, and *n*-butanol are blended into diesel by volume of 80%. Experiments are conducted to investigate the fuel physicochemical property requirement and engine performance under different engine-out NOx levels with the variation of engine speed and load. Meanwhile, the differences in engine performance and emissions when using gasoline and *n*-butanol are compared.

Table 1
Engine specifications.

Engine type	DI In-line 6, water cooled
Bore × Stroke	113 mm × 140 mm
Connecting Rod	209 mm
Displacement	8.42 L
Compression Ratio	16.8
Swirl Ratio	1.25
Injection Nozzle	0.163 mm × 8–148°
Maximum Injection Pressure	180 MPa
Injector flow rate	1380 ml/min
Injection System	Common rail
Number of Valves	4
Max Torque/Speed	1280 N.m/(1200–1700 r/min)
Rated Power/Speed	243 kW/2200 r/min

2. Experimental setup and methods

2.1. Engine and instrumentation

The experimental investigation is conducted on a six-cylinder common-rail HD diesel engine. Some modifications have been made. The original waste-gated turbocharger has been replaced by a newly matched two-stage turbocharger with an inter-stage cooler to ensure a high intake pressure and high turbocharger efficiency. The compression ratio is decreased from 17.5 to 16.8. And, in order to achieve a high EGR rate and an optimum trade-off performance between the gross indicated thermal efficiency (ITE_{gross}) and pumping losses, a dual loop EGR (DL-EGR) system is applied. The ECU is modified, so the control of each EGR valve and each throttle valve is independent from each other. The key specifications of the engine are listed in Table 1. The schematic of the experimental setup is given in Fig. 1. Table 2 shows the specification and measuring accuracy of measurement instruments.

The EGR rate is calculated by the concentrations of carbon dioxide (CO_2%) in the exhaust and intake gas through the following formula:

$$\text{EGR rate}(\%) = \frac{(CO_2\%)_{intake}}{(CO_2\%)_{exhaust}} \times 100 \tag{1}$$

The cylinder pressure is measured using a pressure sensor (Kistler 6125A) with a corresponding charge amplifier and data acquisition system. The pressure data is taken in every 0.5 crank angle degree and the cylinder pressure is the ensemble average of 100 consecutive engine cycles. Gaseous emissions are measured using a gas analyzer (HORIBA MEXA 7100DEGR), which measures THC by a method of hydrogen flame ionization, CO and CO_2 by non-dispersive infra-red, and NOx using a chemiluminescent analyzer. Smoke is measured using a filter paper smoke meter (AVL 415S). The value of smoke is averaged between 5 samples of a 2 L volumes. According to the specification of the soot meter, the specific dry soot can be calculated from the filter smoke number (FSN) by the following formula [39].

$$\text{soot} = \frac{1}{0.405} \times 5.32 \times \text{FSN} \times \exp^{0.3062\text{FSN}} \times 0.001 \times \frac{(m_{air} + m_{fuel})}{1.2929} \times \frac{1}{Pe} \tag{2}$$

where m_{air} and m_{fuel} denote the mass flow rates of intake air and test fuel. *FSN* is the filter smoke number which is measured by the smoke meter. *Pe* is the engine effective power. Through this formula, specific dry soot emissions (g/kW-h) can be calculated.

Since the low heating value (LHV) is different for each test fuel, the equivalent BSFC was used, which was calculated by the following formula: