Energy 97 (2016) 105–112

Contents lists available at ScienceDirect

Energy

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

Improvement of emission characteristics and thermal efficiency in diesel engines by fueling gasoline/diesel/PODEn blends

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ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form
3 November 2015
Accepted 23 December 2015
Available online xxx

Keywords:
Gasoline/diesel/PODEn blends
Diesel engine
Exhaust gas recirculation
Emission characteristics
Thermal efficiency

ABSTRACT

PODEn (polyoxymethylene dimethyl ethers) stand for the mixtures of ethers with the chemical formula $CH_3O(CH_2O)nCH_3$, which have high cetane number and nearly 50% oxygen content. Gasoline/Diesel (GD) blends reduce the soot emissions of diesel engines with the penalty of combustion efficiency. In order to reduce emissions and improve thermal efficiency of diesel engines, blends of GDP (gasoline/diesel/PODEn) were proposed and studied in this work. Experiments were carried out in a diesel engine fueled with pure diesel, GD blends, and GDP blends. The results show that both GD blends and GDP blends have single-stage premixed heat release. GDP blends have shorter ignition delay, lower max pressure rise rate and COV_{IMEP} (coefficient of variation of indicated mean effective pressure) than GD blends. GD blends have lower soot emissions than diesel fuel, while GDP blends have lowest soot emissions and exhibit best NOx-soot trade-off. GDP blends also have higher combustion efficiency and thermal efficiency than GD blends, even slightly higher than diesel fuel.

1. Introduction

Diesel engines, due to the high thermal efficiency and power performance, are widely used in vehicles and engineering machinery. However, with the increasingly strict emission regulation, it's a big challenge for conventional diesel engines to reduce NOx and Soot emissions simultaneously to achieve the emission targets.

The authors have proposed ideas of WDF (wide distillation fuel) to overcome the trade-off of NOx and soot emissions in diesel engine [1–5]. WDF refers to fuels with a wide distillation range from the IBP (initial boiling point) of gasoline to the FBP (final boiling point) of diesel. WDF contains high volatile components which are beneficial for atomization and evaporation. Meanwhile, the ignition delay of WDF is longer than commercial diesel fuel which are important for premixed combustion. In the long term, a single distillation process covering the entire range for gasoline, kerosene, and diesel can be used to produce a novel fuel from petroleum directly. This novel fuel was named FDF (full distillation fuel) [3]. In the short term, direct blending of commercial gasoline and diesel is the most convenient method [6–8] to obtain WDF.

Many researchers have studied GD (gasoline/diesel) blend fuels [9–17]. Previous studies have proved that high gasoline ratio extends the ignition delay and improves fuel volatile which reduces soot emissions, however, the side effects are unstable combustion at low load and low combustion efficiency due to the low ignitability. GD blends with 50% gasoline (GD50) is the optimal choice balancing emission and efficiency, but it still has some shortcomings. Weall and Collings [9] investigated PPCI (partially premixed compression ignition) mode by using GD50 and found wider low-emission operating range compared to diesel. However, high soot emissions at high load and combustion stability issue at low load are the major challenges. Xu et al. [10] applied GD50 in PPCI and achieved low NOx and soot emissions simultaneously at medium load, however, high HC (hydrocarbon) and CO (carbon monoxide) emissions and efficiency reduction were observed. Therefore, low emissions and high efficiency cannot be both achieved only by blending diesel and gasoline, it is necessary to add new components to improve fuel ignitability and further reduce soot emissions.

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http://dx.doi.org/10.1016/j.energy.2015.12.110
0360-5442/

Abbreviations

PODEn	polyoxymethylene dimethyl ethers	COV_{IMEP}	coefficient of variation of IMEP
DMM	dimethoxy methane	WDF	wide distillation fuel
IBP	initial boiling point	DME	dimethyl ether
GD	gasoline/diesel	FBP	final boiling point
D100	pure diesel fuel	GDP	gasoline/diesel/PODEn
GDP30	gasoline/diesel/PODEn blends with 30% PODEn	GD50	gasoline/diesel blends with 50% gasoline
PPCI	partially premixed compression ignition	HC	hydrocarbon
CA10	crank angle of 10% mass fraction burn	EGR	exhaust gas recirculation
SOC	start of combustion	CA50	crank angle of 50% mass fraction burn
CAD	crank angle degree	SOI	start of injection
IMEP	indicated mean effective pressure	ATDC	after top dead center
RoHR	rate of heat release	ECU	electronic control unit
MPRR	maximum pressure rise rate	TDC	top dead center
		LHV	latent heat of vaporization
		CO	carbon monoxide

PODEn (polyoxymethylene dimethyl ethers) are promising fuel additives for diesel engines, which have very high cetane number and nearly 50% oxygen content making them ideal for the purpose mentioned above. PODEn stand for the mixtures of ethers with the chemical formula of $CH_3O(CH_2O)nCH_3$. As coal-based fuel, PODEn can be produced in large volume. In 2013, Zheng et al. [18] developed an industrial process for commercial production of PODEn at 10,000 ton/year scale, and the production cost is similar to that of diesel fuel.

From the analysis above, it is obvious that PODEn show great potential as blending components to improve the shortcoming of GD blends. Meanwhile, the blending ratio of PODEn to GD does not need to be very high because GD blends can also reduce soot emissions. In this work, a comparative study of pure diesel, GD blends, and GDP (gasoline/diesel/PODEn) blends was carried out in a light-duty direct injection diesel engine. The main purpose is to investigate the potentials of achieving high efficiency and low emission combustion by using GDP blends in conventional diesel engines.

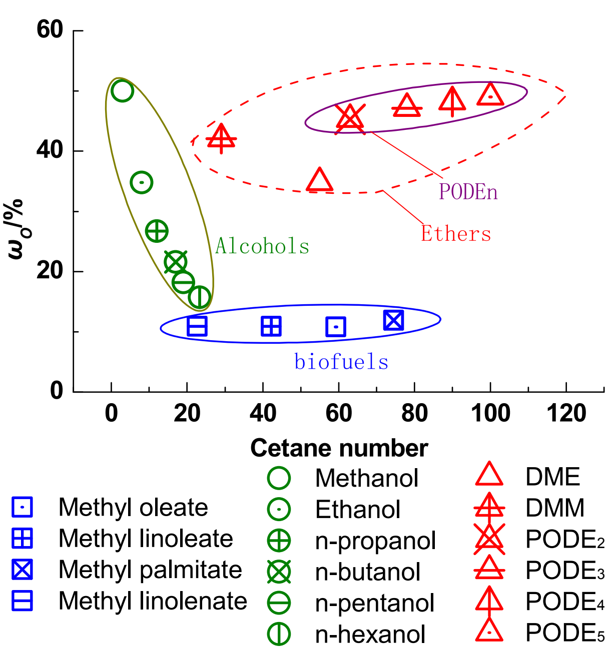

Fig. 1. Cetane number and oxygen content of some oxygenated fuels.

2. PODEn advantages as a blend component for GD blends

In order to improve the combustion efficiency and further reduce soot emissions of GD blends, the new fuel component should have high cetane number and high oxygen content. Fig. 1 compares the cetane number and oxygen content of some commonly used oxygenated fuels. These fuels are divided into three categories: esters, alcohols and ethers.

The components of biodiesels are mostly esters. Due to the long carbon chain, biodiesels have high cetane number and good ignitability. However, there is only one ester group (−COOR) in the molecule of biodiesels, leading to limited oxygen content of about 10%. Biodiesels, when blended at low blending ratio, only reduce soot emissions moderately because soot reduction is highly related to the oxygen content [19].

Due to the low ignitability, methanol and ethanol are usually used as gasoline blending components. Compared with low-carbon alcohols, high-carbon alcohols have higher cetane number and viscosity, thus better compatible with conventional diesel engines. Li et al. [20] investigated pentanol in a diesel engine and found that pentanol reduces NOx and soot emissions with similar efficiency to the diesel fuel. However, the cetane number of pentanol is around 20, which causes significantly higher CO and HC emissions.

Ethers usually have high cetane number though the molecule chains are not long. Because most ethers have multiple CH_2O units, the oxygen content of ether fuels is much higher than that of biodiesels. Meanwhile, the molecule structure of ethers are found more efficient in reducing soot emissions than other structures [21,22]. Therefore, ethers are the optimal choice among the three categories.

Table 1 shows the specific properties of different ethers. DME (dimethyl ether) is a gaseous fuel at standard condition and it is not convenient to be used for diesel engines. DMM (dimethoxy methane) is a liquid fuel, however, the cetane number of DMM is only 29 and experimental results show that DMM and diesel blends are prone to cause vapor lock [23]. Among all PODEns, $PODE_2$ does not fulfill the security criterion due to its low flash point [24], and if n is higher than 5, melting points are too high. Therefore, only $PODE_3$, $PODE_4$, and $PODE_5$ are ideal blending components for engine fuels.

The PODEn tested in this work was synthesized and separated by Yuhuang Company, which has a mass distribution of $PODE_2$:$PODE_3$:$PODE_4$ = 2.553%:88.9%:8.48%. The content of $PODE_2$ is too small to have adverse effect on security risk, the major