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Full Length Article

An experimental investigation on thermal efficiency of a compression ignition engine fueled with five gasoline-like fuels

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HIGHLIGHTS

- Five gasoline-like fuels were tested with PPCI and MPCI modes.
- Gasoline/PODE fuel achieved highest thermal efficiency of about 48.8% for both modes.
- NOx and soot emissions were lower than the limit of Euro VI standard in PPCI mode.

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ABSTRACT

Partially Premixed Compression Ignition (PPCI) and Multiple Premixed Compression Ignition (MPCI) are two high efficiency and clean combustion strategies. This paper presents an experimental investigation on the efficiency of PPCI and MPCI combustion using five gasoline-like fuels: gasoline, gasoline/ethylhexyl-nitrate (EHN) blends, gasoline/diesel blends, gasoline/polyoxymethylene dimethyl ethers (PODEn) blends, gasoline/diesel/PODEn blends, denoted as G, GE, GD, GP, GDP, respectively. The study was conducted using a single cylinder engine that was retrofitted from a production Euro IV diesel engine. The results showed that in PPCI mode, the order of thermal efficiency from the highest to the lowest was GP, G, GDP, GE, and GD, while the order in MPCI mode was GP, GDP, GE, G, and GD. The thermal efficiency of MPCI mode was higher than that of PPCI mode, except for GP, whose thermal efficiency was the highest of about 48.8% for both modes due to the early CA50 and short combustion duration. In PPCI mode, NOx and soot emissions were below 0.4 g/kWh and 0.01 g/kWh, respectively, satisfying the Euro VI emission standard. NOx emission in MPCI mode can meet the requirement of Euro VI. However, the soot emission exceeded the limit because the second stage combustion was partially diffusion combustion, implying an extra Gasoline Particle Filter (GPF) was needed to meet the Euro VI standard. This study indicates that PPCI injection strategy alone and MPCI injection strategy with GPF are two potential ways of retrofitting a Euro IV engine to meet the Euro VI emission standard. GPF increases manufacturing cost, but higher thermal efficiency in MPCI mode could reduce the total cost of ownership due to the lower fuel consumption.

1. Introduction

Gasoline spark ignition engines have low thermal efficiency due to low compression ratio and high pumping loss [1]. Because of the low volatility and short ignition delay of diesel, which makes it difficult to organize high percentage of premixed combustion, diesel compression ignition engines have high NOx and soot emissions. In order to improve engine efficiency while reducing pollutant emissions, various combustion strategies have been investigated, such as Homogeneous Charge Compression Ignition (HCCI),

Abbreviations: PPCI, partially premixed compression ignition; EHN, ethylhexyl-nitrate; HCCI, homogenous charge compression ignition; TDC, top dead center; GCI, gasoline compression ignition; IMEP, indicated mean effective pressure; COV, coefficient of variation; LHV, lower heating value; SOI, start of injection; HC, hydrocarbon; ISNOx, indicated specific nitrogen oxides; MPCI, multiple premixed compression ignition; PODEn, polyoxymethylene dimethyl ethers; GPF, gasoline particle filter; EGR, exhaust gas recirculation; RON, research octane number; MPRR, maximum pressure rise rate; CAD, crank angle degree; HRR, heat release rate; ITE, indicated thermal efficiency; CO, carbon monoxide.

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Partially Premixed Compression Ignition (PPCI), Multiple Premixed Compression Ignition (MPCI), etc. HCCI was first studied by Najt [2]. As shown in Fig. 1, homogeneous mixture made by injecting fuel in the intake stroke leads to fast combustion near TDC, which results in high thermal efficiency and low NOx and soot emissions. However, the control of HCCI combustion is a challenge and high pressure rise rate causes high combustion noise. The concept of Gasoline Compression Ignition (GCI) was first proposed by Kalghatgi [3] to take advantage of good volatility and long ignition delay of gasoline fuel and high compression ratio of diesel engine to achieve high efficiency and low emissions simultaneously. Later, Kalghatgi et al. [4] proposed PPCI combustion. By injecting fuel in the compression stroke, mixture stratification is formed before combustion. PPCI mode can extend load range while maintaining high thermal efficiency and low NOx and soot emissions. However, the pressure rise rate is still too high at high load. Yang et al. [5] proposed MPCI combustion mode to control the combustion noise by organizing injection and combustion process in a sequence of "spray – combustion – spray – combustion". MPCI mode can extend load range with acceptable pressure rise rate.

The GCI fuels can be sorted into two categories, high octane fuels and low octane fuels. High octane fuels usually refers to gasoline with octane number greater than 90. Some researchers also studied GCI combustion of gasoline-ethanol blends [6–8]. Compared with high octane fuels, low octane fuels have better ignitability and can extend GCI operation range to lower load. Naphtha is a typical low octane fuel studied in different GCI modes [9,10]. Another common method to obtain low octane fuels is to blend gasoline with diesel [11,12]. Some researchers also studied the GCI combustion of gasoline and highly oxygenated fuel blends, such as polyoxymethylene dimethyl ethers (PODEn). PODEn are the mixture of ethers with the chemical formula of $CH_3O(CH_2O)_n$-CH_3, which have high cetane number and near 50% oxygen content, and are used to improve ignitability and reduce soot emission [13–16]. Compared to other oxygenated fuels (e.g. cyclohexanone [17], ethanol [6–8]), high cetane number of PODEn would better enhance the ignitability of the blended fuel, leading to low CO and HC emissions and thus high combustion efficiency. What's more, near 50% oxygen content in PODEn contributes to the soot oxidation process and therefore leads to less soot emission.

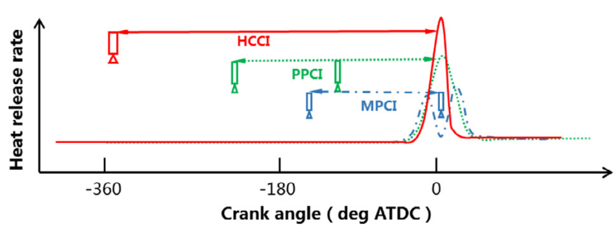

Fig. 1. Schematic diagram of HCCI [2], PPCI [4], MPCI [5].

In this study, five gasoline-like fuels (market gasoline, gasoline/ethylhexyl-nitrate (EHN) blends, gasoline/diesel blends, gasoline/PODEn blends, gasoline/diesel/PODEn blends, denoted as G, GE, GD, GP, GDP, respectively) were studied with different combustion modes to explore the highest achievable thermal efficiency while maintaining engine-out NOx emission below 0.4 g/kWh.

2. Experimental setup

2.1. Apparatus

The study was conducted using a single-cylinder, four-stroke, water-cooled, direct injection diesel engine, which was retrofitted from a Euro IV four-cylinder engine by deactivating cylinders 2–4. Fig. 2 shows the schematic of the experimental setup. The engine specifications are listed in Table 1. The turbocharger was removed and an external air compressor was used for intake boost. The intake and exhaust surge tanks were used to reduce air flow pulsation and decrease the measurement uncertainties of air flow, intake pressure, and exhaust pressure. The uncertainties of the experimental equipments are listed in Table 2. Cooled EGR was employed and EGR ratio was calculated with formula (1).

$$EGR\% = \frac{m_r}{m_r + m_{in}} \times 100\% \quad (1)$$

where m_r and m_{in} are the mass of EGR air and intake fresh air, respectively.

The in-cylinder pressure was measured with an AVL GH14P cylinder pressure transducer. Data of 100 consecutive cycles were recorded for combustion analysis. Exhaust emissions, including CO, HC, CO_2, NOx, were measured by AVL CEB II pollutants analyzer. AVL 439 opacimeter was used for soot emission measurement and the measurement unit is m^{-1}. According to the user guide of the soot emission measurement devices, the indicated specific soot emission can be calculated using formulas (2)–(4).

$$N = 100 \times (1 - e^{-0.43k}) \quad (2)$$

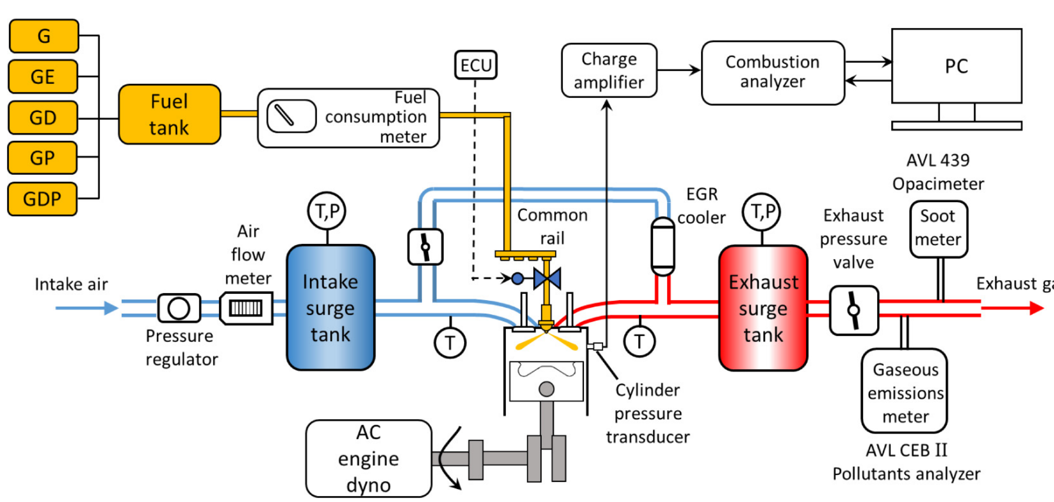

Fig. 2. Schematic of experiment bench.