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Gasoline compression ignition operation on a multi-cylinder heavy duty diesel engine

Bin Mao, Peng Chen, Haifeng Liu, Zunqing Zheng, Mingfa Yao*

State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

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ABSTRACT

Gasoline compression ignition (GCI) is a promising combustion concept with high thermal efficiency, low emissions, and minimal modification of standard engine hardware. With a relaxed constraint on the engine-out NOx emissions, different GCI operating parameters such as exhaust gas recirculation (EGR), injection timing, injection pressure, pilot-main injection interval, and pilot mass were swept to find their optimal calibrations. The entire operating map of a heavy duty diesel engine using GCI combustion with multi-injection strategies was also investigated. Results show that the use of pilot injection is effective in controlling the premixing heat release rate, reducing the combustion noise and emissions, and improving controllability, and allows for advancing combustion timing within the imposed mechanical constrains. With the engine-out NOx calibration of around 4.5 g/kW-h for typical Euro 6 compliant engines, the double injection strategy is applied over the entire operating map in GCI mode, and similar engine performance and emissions can be achieved by GCI combustion compared to conventional diesel combustion (CDC) mode, just using lower injection pressures. The peak brake thermal efficiency (BTE) of 44% over the entire operating map is demonstrated with minimal pumping and friction losses while keeping the peak cylinder pressure (PCP) within 16 MPa.

1. Introduction

US Environmental Protection Agency (EPA) initiates rulemaking for low-NOx emission standards for heavy duty on-road engines reducing NOx emission limit by 90% to 0.020 g/bhp-hr (0.027 g/kW-h), which would be implemented in Model Year 2024 [1]. This timeframe is aligned with a milestone implementation year for the EPA heavy duty Phase 2 Greenhouse Gas (GHG) program [2]. Therefore, the regulatory requirements to lower both criteria of pollutants and greenhouse gases from heavy duty engines are driving new perspectives on the interaction between fuels and engines. Gasoline and diesel fuel are both petroleum-derived liquids that come from the fractional distillation and refining of crude oil. In comparison with diesel fuel, gasoline fuel is more volatile and resistant to auto-ignition, because it is typically composed of relatively small branched or cyclic hydrocarbons with high bond strength. With regard to Low Temperature Combustion (LTC) operability, fuel volatility and chemical reactivity have a great impact on the in-cylinder processes [3,4]. The idea of GCI was first proposed by Johansson et al. [5] and Kalghatgi et al. [6]. GCI has drawn extensive attention of researchers in the past decade, and variations on GCI concept are explored, with key differences being the fuel delivery strategy.

Dempsey et al. reviewed the GCI operating strategies in the perspective of in-cylinder fuel stratification, and identified three representatives: partial, moderate, and heavy fuel stratifications (PFS, MFS, and HFS) [7]. For PFS and MFS, the mixing between fuel and air is very easy due to the early injection and the long ignition delay (ID). Hence, there is great scope for reducing the injection pressure requirement and the cost of the injection system compared to modern diesel engines [8,9]. However, PFS operation tends to display the same challenges as homogenous charge compression ignition (HCCI) because they are both kinetically controlled. And the compression ratio of PFS and MFS operations is commonly lower than CDC level for the better controlling of combustion noise and premixing charge [10,11]. Additionally, moderate combustion efficiency is another challenge to thermal efficiency improvement. From the fuel economy point of view, HFS usually achieves the highest BTE due to low combustion loss, short combustion duration (CD), and high compression ratio [12]. Gasoline Partially Premixed Combustion (PPC) is a typical HFS mode with an injection-driven combustion process [13]. Injection events can be delayed to slightly before the TDC (BTDC) and utilize high fuel injection pressure to complete the fuel injection events before auto-ignition [14]. The gasoline fuel property, high injection pressure, and strict dilution ratio control with air and exhaust is the key enablers of its efficient

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* Corresponding author.
E-mail address: y_mingfa@tju.edu.cn (M. Yao).

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Nomenclature

GCI	gasoline compression ignition
CDC	conventional diesel combustion
BTE	brake thermal efficiency
PCP	peak cylinder pressure
RI	ringing intensity
EPA	Environmental Protection Agency
GHG	greenhouse gas
LTC	low temperature combustion
PFS	partial fuel stratification
MFS	moderate fuel stratification
HFS	heavy fuel stratification
HCCI	homogenous charge compression ignition
ID	ignition delay
TDC	top dead center
CD	combustion duration
PPC	partially premixed combustion
EGR	exhaust gas recirculation
ITEgross	gross indicated thermal efficiency
ISFCnet net	indicated specific fuel consumption
MPRR	maximum pressure rise rates
HRR	heat release rate
SCR	selective catalytic reduction
SET	supplemental emissions test
BMEP	brake mean effective pressure
DL-EGR	dual loop EGR
VGT	variable geometry turbocharger
FSN	filter smoke number
ESC	European stationary cycle
LPL-EGR	low pressure loop EGR
CA10	crank angle at which 10% completion of heat release
SOI	start of injection
S_{ID}	sensitivity of the ignition delay
COV	coefficient of variation
LHV	lower heating value
CA50-90	the interval between CA50 and CA90
CO	carbonic oxide
HC	hydrocarbon
SOI_p	start of the pilot injection
SOI_m	start of the main injection
BSFC	brake specific fuel consumption
CA50	crank angle at which 50% completion of heat release
ATDC	after top dead center
RCCI	reactivity controlled compression ignition

clean combustion [14].

The efficiency improvement of HPS concept is also facing a series of challenges. For multiple considerations in improving indicated fuel efficiency and controlling engine-out emissions, gasoline PPC requires approximately 45–55% of EGR rates combined with a lambda of nearly 1.4 [15,16]. While gross indicated thermal efficiency (ITEgross) improves with increasing intake dilution ratio, the required pumping work may decrease the BTE at EGR rates above 40% [17–19]. If further EGR rates are needed for future NOx emission standards (0.02 g/hp-hr), the match of air system will be more complicated and the increased pumping losses and heat transfer losses will impose more adverse effects on BTE [19]. The dependence of high-load PPC operation on injection pressure is lower than diesel Premixed Charge Compression Ignition (PCCI) but significantly higher than conventional Euro 6 diesel engine [14,20–22]. This is not conducive to reliability of fuel system and friction loss control [23]. Hence, the researchers attempt to transfer the PPC concept into a production viable engine with brake efficiencies higher than state of the art heavy duty diesel engines have been blocked by air system match, fuel system performance, and high mechanical challenge [24]. Tuner claims that the best compromise between lambda, EGR rate, turbocharger efficiency, NOx level, and after-treatment of gasoline PPC needs to be investigated further [18].

From the perspective of industrial engineers, increasing the efficiency of after-treatment systems is considered to be an important technical routine to increase efficiency of heavy duty diesel engines due to the inherent trade-off between fuel efficiency and engine-out NOx. For CDC mode, typical engine-out NOx emissions for Euro 6 and EPA 2010 compliant engines are calibrated to about 4.3 g/kW-h and 3.0 g/bhp-hr (4.0 g/kW-h), respectively [25,26]. Daimler Trucks, as an industry team in the SuperTruck Project aiming to maximize BTE values, further reduces the EGR rates to relax the Supplemental Emissions Test (SET) averaged engine-out NOx level to 6.9 g/bhp-hr (9.2 g/kW-h) [27]. The reduced EGR flow combined with a resized turbocharger enables improvements in gas flow optimization including lower differential pressure in the EGR loop and increased turbocharger efficiency [25]. Furthermore, the NOx increase also aids the passive soot regeneration in diesel particulate filter (DPF) and reduces the frequency of active regeneration events. Similarly, as to the low temperature dual fuel combustion mode, Hanson et al. [28,29] report works on combining the kinetically and mixing-controlled dual fuel combustion strategies through decreasing the EGR rate and increasing the fuel stratification level of diesel injection, which provides a method to increase the peak load capability without increasing the MPRR. Non-EGR reactivity controlled compression ignition (RCCI) receives a remarkable BTE absolute benefit of 2% compared with the typical RCCI with extremely low engine-out NOx emissions.

Based on the discussions above, gasoline HPS concepts originally designed to produce low engine-out emissions should therefore also explore additional technical routines to deliver comparable efficiencies as CDC modes and remain competitive. While relaxing the engine-out NOx target, a selective catalytic reduction (SCR) can be in charge of the NOx abatement. Hence, the requirement of air and exhaust dilution ratios and fuel injection pressure can be lowered. Additionally, the fuel stratification can be further increased to improve the low-load stability, and the premixing ratio and the pressure rise rate can be reduced correspondingly. This kind of mixing-controlled GCI mode combines the soot advantage of gasoline-like fuels with high thermal-dynamic efficiency of CDC modes. Zhang et al. [22] investigate the combustion characteristics and emissions of naphtha fuels in a Cummins six-cylinder heavy duty truck engine. Utilizing the soot benefit of naphtha fuels, the engine can be calibrated to lower engine-out NOx emission levels across the SET operating points without changing the injection strategy while maintaining soot-free operation with good fuel efficiency. Some of low-octane-number gasoline fuels are, however, not expected to be commercially available on the short term. Therefore, exploring the efficiency potential of commercial gasoline fuels under mixing-controlled mode is one of the main objectives of this work.

The early pilot injection applied in gasoline PPC operation is to inject an amount of fuel at around 60 °CA BTDC, then add EGR to prevent auto-ignition during the compression stroke [16]. While the close pilot injection is a small quantity of fuel injected prior to the main injection, which has long been used in diesel engines as a means to reduce combustion noise. As to the gasoline HFS concept with low EGR rates, the use of close pilot injection increases the fuel stratification level and is more preferable in combustion process control and prevents fuel from adhering to the cylinder wall. The combustion of pilot fuel increases temperatures and releases radical concentrations, and therefore decreases the ignition delay of main injection fuel, thus leading to a reduction in premixing ratio and combustion noises [30]. The effect of close pilot injection on combustion process control varies according to