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Research Paper

Experimental investigations of gasoline partially premixed combustion with an exhaust rebreathing valve strategy at low loads

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HIGHLIGHTS

- Effects of injection timing, i-EGR and intake pressure on PPC at low loads are investigated.
- The operating region for high-efficient, clean and stable combustion is explored.
- Higher i-EGR rate is required to maintain stable PPC at lower loads.
- Intake boosting has the potential to further extend the PPC low-load limit.
- Stable PPC at 1.5 bar gross IMEP can be achieved with optimal control strategies.

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ABSTRACT

This paper investigates the combustion and emission characteristics using a commercial gasoline with Research Octane Number (RON) of 93 on a Partially Premixed Combustion (PPC) engine equipped with a Variable Valve Actuator (VVA) system. The effects of injection timing, internal exhaust gas recirculation (i-EGR) rate and intake pressure on combustion and emissions are studied. The i-EGR was achieved by an extra opening of the exhaust valve during the intake process. The study was conducted at an engine speed of 1500 r/min with cyclic fuel mass from 11.6 to 22.2 mg. The operating region for high-efficient, clean and stable gasoline PPC (i.e., $COV_{imep} < 5\%$, $NO_x < 0.4$ g/kW h, Smoke < 0.1 FSN, CO and HC as low as possible) was explored and discussed. The results illustrate that proper i-EGR rates with a fixed injection timing of −24°CA ATDC could maintain optimal thermal efficiency while minimizing CO and HC emissions as the engine load decreased from 3.9 to 2.1 bar gross indicated mean effective pressure ($IMEP_g$). However, high NO_x at higher load was observed and the adoption of earlier injection timing with lower i-EGR rate has the potential to suppress the sharp Smoke increase at lower NO_x levels. Improved combustion process can be obtained with later SOI timings as well as higher i-EGR rates as the intake pressure increased. It has been found that the low-load limit of stable gasoline PPC can be extended to 1.5 bar $IMEP_g$ through the optimization of VVA, injection strategy and intake boosting.

1. Introduction

Diesel engines have higher thermal efficiency than spark-ignition and gas engines due to their high geometry compression ratio and no throttling losses. However, the high cetane number and low volatility of diesel-type fuels lead to inadequate fuel-air mixing before the start of combustion (SOC), especially at higher loads. Locally rich and high-temperature regions are formed, resulting in high nitrogen oxides (NO_x) and soot emissions, which are difficult to control simultaneously.

Compared with diesel-type fuels, gasoline-like fuels exhibit longer ignition delays and a better fuel-air mixing process can then be achieved due to their higher volatility and auto-ignition resistance [1–3]. Recently, replacing diesel-type fuels with gasoline-like fuels in compression ignition engines has attracted increasing attention. As one of the clean combustion modes, Homogeneous Charge Compression Ignition (HCCI) can realize high thermal efficiency as well as low NO_x and soot emissions. However, the applicable load range of the gasoline HCCI combustion is limited due to its difficulty in auto-ignition timing and combustion phasing control [4]. In contrast, a wider load range of clean combustion can be obtained with gasoline Partially Premixed Combustion (PPC) mode by controlling the SOC timing with the injection event

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Nomenclature

ATDC	after top dead center	ITE_g	gross indicated thermal efficiency
BMEP	brake mean effective pressure	$IMEP_g$	gross indicated mean effective pressure
CA50	crank angle corresponding to 50% accumulative heat release	L	valve opening duration
°CA	degree crank angle	MPRR	maximum pressure rise rate
λ	excess air coefficient	NVO	negative valve overlap
EGR	exhaust gas recirculation	NO_x	nitrogen oxides
e-EGR	external exhaust gas recirculation	PPC	partially premixed combustion
H	valve opening height	ROHR	rate of heat release
HCCI	homogeneous charge compression ignition	SOI	start of injection
i-EGR	internal exhaust gas recirculation	SOC	start of combustion
		VVA	variable valve actuator

and by separating the injection event from the combustion process [5,6]. In addition, the high-load limit of PPC can be further extended by reducing the maximum pressure rise rate (MPRR) with multiple-injection strategy [7–9]. However, there are still some problems at low loads need to be solved for gasoline-like fuels due to their low reactivity. Recent studies [10–14] have shown that fuels with Research Octane Number (RON) greater than 96 do not allow to run below 2 bar gross indicated mean effective pressure ($IMEP_g$) at low NO_x levels of 0.4 g/kW h (i.e., to meet the Euro VI standards) unless the intake temperature is higher than 117 °C. Although lower RON helps to improve the combustion stability at low loads, it is also confronting with heavy pre-ignition and hard knock at high loads. In order to extend the low-load limit without the need to change fuel characteristics, various technologies have been developed and employed to increase the fuel-air mixture's reactivity at low loads.

Weall and Collings [15] explored low-load operation (1 and 2 bar brake mean effective pressure, BMEP) on a gasoline PPC engine equipped with an intake air heater by sweeping the intake temperature from 70 to 96 °C, intake pressure from 0.8 to 0.96 bar, single injection timing from −30 to −10 degree crank angles (°CA) after top dead center (ATDC), as well as double injections with various duration ratios and separations. It was found that increase in intake temperature, intake pressure and fuel stratification could help to improve the combustion stability for RON 95 gasoline fuel. Exhaust gas recirculation (EGR) was not used in their study and NO_x was controlled by increasing the premixing with earlier single-injection or double-injections. However, sharp increases in both CO and HC emissions were observed. Solaka et al. [16] studied the effect of the excess air coefficient (λ) on the low-load limit for PPC with an intake temperature of 62 °C and external boosting. It was demonstrated that as λ was increased from 1.5 to 7.4 while maintaining a high intake pressure at around 2.2 bar, the low-load limit for RON 89 fuel could be extended from 7 to 2 bar $IMEP_g$; however, NO_x emission also increased sharply because of the higher oxygen concentration. In addition, the additionally required energy for the application of these strategies also has adverse effects on thermal efficiency. Desantes et al. [17] investigated the applicable load (equivalence ratio) range on a spark assisted PPC engine with different injection timings, injection pressures, intake oxygen concentrations and double-injections. The results showed that the spark assistance effectively extended the low-load limit to about 3 bar IMEP for RON 98 gasoline fuel. Compared to the late SOI timing of −9°CA ATDC, higher combustion efficiency and thermal efficiency can be obtained with an early SOI timing of −24°CA ATDC combined with a higher injection pressure, however, penalized NO_x emission was also observed. Lower NO_x emissions could be achieved with lower intake oxygen concentrations (higher EGR rates); however, the thermal efficiency deteriorated with more incomplete combustion losses. Benajes et al. [18] evaluated the influence of spark assistance on combustion stability and cycle-to-cycle control for RON 98 gasoline fuel under an intake pressure of 1.6 bar. It was shown that stable combustion was obtained with the spark assistance at around 4 bar IMEP, which was not possible without the spark assistance. As the load was further reduced to 2 bar IMEP, only five out of ten engine cycles were ignited, even after using the spark assistance. Subsequent studies in Refs. [19,20] indicated that the use of double-injections in combination with spark assistance could obtain a better fuel-air mixture distribution and showed high potential for low-load extension; however, loads lower than 3 bar IMEP were not reported.

Borgqvist et al. [21] investigated the low-load limit of gasoline PPC with RON 87 gasoline fuel on a light-duty diesel engine equipped with a Variable Valve Actuator (VVA) system. The results showed that the trapped hot residual gases with negative valve overlap (NVO) had a positive effect on low-load extension and a minimum attainable load of 1.75 bar $IMEP_g$ could be obtained. However, low thermal efficiency with NVO was also observed due to the increased heat transfer losses raised by the re-compression of the residual gases. Thus it was suggested that less NVO should be used to improve the thermal efficiency. Tanov et al. [22] studied the degree of combustion stratification with different injection strategies and NVO settings on an optical engine at very low load (towards idling). It was found that the combustion with single-injection was more stratified than with double-injections or triple-injections, which was beneficial to accelerate the combustion process. As an alternative to NVO, the exhaust rebreathing valve strategy has higher thermal efficiency due to its higher gas-exchange efficiency [23]. However, the challenge of the rebreathing valve strategy is combustion stability at loads lower than 2 bar IMEP, because the temperature requirement is higher than what can be obtained. Also, high Smoke emissions at loads higher than 2.5 bar IMEP are usually observed due to the low oxygen concentration for NO_x control [23]. Thus, an external exhaust gas recirculation (e-EGR) strategy should be employed at higher loads to suppress the accelerated combustion rate and NO_x emission [24].

Although previous studies have been focusing on low-load extension with the exhaust rebreathing valve strategy, few of them have paid attention to the combined effects of injection timing, intake pressure and the internal exhaust gas recirculation (i-EGR) rate on the combustion and emission characteristics of gasoline PPC at low loads. Thus, the applicable load has been limited to a very narrow range and the potential of the exhaust rebreathing valve strategy for low-load extension has not been fully explored yet. Therefore, further studies are still necessary to extend the understanding of gasoline PPC with various control strategies, then a combined systemic strategy for gasoline PPC low-load extension can be proposed.

Therefore, this paper focuses on gasoline PPC low-load extension with various control strategies, including i-EGR achieved by