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Trade-off on fuel economy, knock, and combustion stability for a stratified flame-ignited gasoline engine

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HIGHLIGHTS

- Combining port and direct injections improved fuel economy of spark-ignited auto-ignition combustion.
- Higher direct fuel injection fraction (when < 35%) advances the combustion phasing.
- Four zones were defined to show effects of direct fuel injection timing on the combustion.
- An online optimization method was developed for the direct fuel injection timing.

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ABSTRACT

A combination of port fuel injection (PFI) and direct injection (DI), called P-DI strategy, was used in a four-cylinder gasoline engine. The aim was to achieve a stratified flame ignition (SFI) hybrid combustion and manage the trade-off among fuel economy, knock, and combustion stability (EKS) in a gasoline engine. In the proposed P-DI strategy, DI was used to enrich the local mixture around the spark plug to enhance the early spark-ignition combustion. On the other hand, PFI was used to form a largely lean homogeneous mixture to achieve a moderately controlled auto-ignition combustion in the outer region of the cylinder. The effects of DI fraction (R_{DI}) and start of injection (SOI) timing of DI on the SFI hybrid combustion were investigated experimentally. It was found that an increased R_{DI} resulted in a parabolic-like effect on the combustion phasing and combustion stability. The earliest combustion phasing was achieved with an R_{DI} of approximately 35%. The fuel economy deteriorated monotonously with increasing R_{DI}. In comparison, the effect of SOI on the SFI hybrid combustion was more complicated. It was found that an SOI between 50°CA before top-dead-center (BTDC) and 90°CA BTDC showed a potential to achieve a satisfactory trade-off among EKS. Based on the above findings, a cost function (J) was proposed to represent the EKS trade-off and reduce the calibration burden for optimal SOI at different engine operating conditions. An extremum-seeking algorithm was adopted to search for the maximum value of J and obtain the optimal SOI timing at each operating point. The proposed algorithm was then validated by experimental results.

1. Introduction

A controlled auto-ignition (CAI) combustion process [1] has the potential to simultaneously reduce both fuel consumption and nitrogen oxide emissions. However, this process is very sensitive to operating conditions [2], which limit the operating range [3–5] of this combustion mode. The spark-ignition (SI)–CAI hybrid combustion [6–8] is a promising solution, because it can initiate combustion with a slow flame propagation followed by a rapid multi-site auto-ignition. By employing the SI–CAI hybrid combustion, the upper load limit can be extended [7,9] and a smooth transition between SI combustion and CAI combustion can be achieved [7,9–11]. The effects of spark timing (ST) [12,13], intake temperature [14], and dilution charge [15] on the hybrid combustion process were also widely investigated. Despite the aforementioned benefits, the upper load limit of the SI–CAI hybrid combustion is still limited due to the unacceptable maximum pressure rise rate (PRR_{max}) at some loading conditions with homogenous in-cylinder mixture [9]. Retarding the combustion phasing can reduce PRR_{max}; however, it can increase cyclic combustion variations [9,15,16] as a retarded combustion is not robust enough to accommodate cycle-to-cycle variations of in-cylinder conditions [17]. In addition, an over-retarded combustion phasing would also lead to fuel

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Nomenclature

ATDC	after top dead center
BTDC	before top dead center
CA	crank angle
CA10	crank angle at 10% total heat release
CA50	crank angle at 50% total heat release
CAI	controlled auto-ignition
COV	coefficient of variation
DI	direct injection
EGR	exhaust gas recirculation
eEGR	external exhaust gas recirculation
EKG	early kernel growth
EKS	fuel economy-knock-combustion stability
EVC	exhaust valve closing
ES	extremum seeking
MFB	mass fraction burnt
HRR	heat release rate
IMEP	indicated mean effective pressure
IVC	intake valve closing
J	the proposed cost function for injection timing optimization
NVO	negative valve overlap
P-DI	port-direct injection
PFI	port fuel injection
PRR	pressure rise rate
R_{DI}	the fraction of fuel mass from DI in the total fuel mass
SFI	stratified flame ignition
SI	spark-ignition
ST	spark timing
SOI	start of injection (for direct injection)
Vs	engine displacement volume
η_i	indicated thermal efficiency
τ	time constant
σ_i	parameters for calibration in the proposed cost function

Subscript

DI	direct injection
ES	extremum seeking
FF	feedforward control
FB	feedback control
HP	high pressure
LP	low pressure
max	the maximum value

penalty.

In order to address the aforementioned trade-off among fuel economy, PRR_{max} (which is a simplified indication of knock intensity), and combustion stability, denoted as economy-knock-stability (EKS) trade-off, previous investigations were performed from two aspects: (1) to understand the causes of combustion instability and (2) to seek an effective solution for the EKS trade-off.

Reuss et al. [18] found that an early kernel growth (EKG) period played a dominant role in the combustion phasing variation for SI-CAI hybrid combustion based on the results at 2000 rpm and 2 bar indicated mean effective pressure (IMEP) on an optical engine. Using the same data from Reuss et al. [18], Natarajan et al. [19] suggested that the fuel/air distribution and its velocity at the vicinity of the spark plug were crucial for a stable combustion in the EKG period. By using three-dimensional computational fluid dynamics simulations, Wang et al. [20] demonstrated that the flame propagation and subsequent auto-ignition were sensitive to the in-cylinder turbulent kinetic energy level and the mean flow velocity around the spark plug at 1500 rpm and 3.6 bar IMEP. Experimental results from Chen et al. [21] indicated that the maximum cyclic combustion variation occurs in the initial heat release phase, as measured by the crank angle of 10% accumulated heat release (CA10) at 1500 rpm and 6 bar IMEP. Hellstrom et al. [22] and Yoshizawa et al. [17] suggested that the cyclic coupling of in-cylinder states, such as the thermal energy and unburned fuel, is the main cause [22] of combustion variation. Those findings indicated the potential for stabilizing the SI-CAI hybrid combustion by enhancing the initial flame propagation process.

Fuel stratification is one of the most effective solutions [3,23] to address the EKS trade-off by increasing the combustion duration with a lower knock intensity. Yun et al. [16] applied a dual-pulse direct injection (DI) to achieve fuel stratification with a largely stoichiometric air–fuel mixture and found that the trade-off between combustion noise (related to knock intensity) and combustion stability can be slightly improved. However, the authors found that retarding the second DI with a fixed fuel rate could deteriorate the fuel economy. In addition, they also found that soot and carbon monoxide emissions were monotonically increased as the second injection timing was retarded [16]. Similarly, the dual-pulse DI was also adopted by Yoshizawa et al. [17] to achieve the so-called two-phase combustion with a largely lean air–fuel mixture, which was shown to be effective in preventing knocks. Despite the benefit of the dual-pulse DI, pure DI showed a higher particulate number emission compared to port fuel injection (PFI), as indicated in the experimental study reported in [24].

In addition to the DI strategy, a combined PFI and DI (P-DI) strategy was applied in a gasoline engine to enable a stratified flame ignition (SFI) hybrid combustion [25,26]. In the proposed SFI hybrid combustion concept, DI was used to form a rich mixture around the spark plug in the central region of the combustion chamber and stabilize the flame kernel formation and initial flame propagation. On the other hand, PFI was used to provide a lean homogenous mixture in the peripheral region and achieve a relatively moderate CAI combustion process [25,26]. The moderate heat release rate (HRR) of the SFI hybrid combustion would reduce the risk of knocking and offers a potential to improve the fuel economy by advancing the combustion phasing. In addition, as a part of the fuel is provided by PFI in the P-DI strategy, the soot emission could be reduced due to a more homogeneous fuel–air mixture in the cylinder compared to that of the pure DI strategy [24,27]. Meanwhile, the fraction of fuel mass from DI (R_{DI}) in the total fuel mass and the corresponding start of injection (SOI) timing of DI in the P-DI strategy can be varied to control the SFI combustion process [28].

As discussed in the above literature review, although the SFI combustion concept has been proposed to stabilize the SI-CAI combustion in gasoline engines [25,26], there is still a lack of experimental investigation on the benefits of the P-DI strategy over the pure PFI and pure DI strategies. Most importantly, there is a gap between the concept of SFI hybrid combustion and its practical application to the engine where an advanced control algorithm is required in order to tackle the complex control problems in SFI hybrid combustion. Therefore, the SFI hybrid combustion achieved using the P-DI strategy is compared with the SI-CAI hybrid combustion achieved using the pure PFI and DI strategies in a four-cylinder gasoline engine. Then, the effects of the DI fraction and the SOI timing of DI on the EKS trade-off of SFI hybrid combustion by using the P-DI strategy are investigated in detail. To realize the SFI hybrid combustion in a real engine application, a cost function is proposed to mathematically describe the EKS trade-off of the SFI hybrid combustion and address the complexity in the calibration of the optimal SOI timing. Using the proposed cost function, an online optimization algorithm is developed based on an extremum seeking (ES) algorithm [29], which is used to seek the corresponding optimal