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An investigation of multiple spark discharge using multi-coil ignition system for improving thermal efficiency of lean SI engine operation

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HIGHLIGHTS

- Effective spark discharge energy exists, which influences on the combustion phasing.
- Too strong spark discharge energy leads to knocking combustion.
- Different spark discharge characteristics are observed for lean SI operation.
- Initial and main combustion phasing can be advanced by the multiple spark discharge.
- Thermal efficiency of SI engine is mainly improved by shortening combustion duration.

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ABSTRACT

Lean spark ignition (SI) engine operation can provide improvement of the thermal efficiency relative to that of stoichiometric SI operation. However, the cycle-to-cycle variations of SI combustion increase with increasing air dilution, and become unacceptable. To gain the benefits of lean operation, the ability to ensure stable, complete and fast combustion is required. As a method to enable stable lean operation, this study investigates the effects of multiple spark discharge on lean SI operation using a multi-coil ignition system that features ten spark coils for a single spark plug.

First, the effects of multiple spark discharge on the combustion phasing and the combustion duration are examined for lean operation (excess-air ratio (λ) = 1.67) under a constant spark timing. The results show that both the total discharge duration and the total discharge energy increase with the extension of time interval between spark discharges (Δt_i) for multiple spark discharge. For the multiple spark discharge of substantially extended Δt_i, a number of restrikes occur after the spark blowouts due to the weak discharge energy release rate. However, both the total discharge duration and the total discharge energy do not contribute directly to the change of initial combustion phase. Instead, the effective spark discharge energy exists within the total discharge energy, which actually contributes to the change of initial combustion phase. When the effective spark discharge energy is high, it leads to the advancement of the initial combustion phase, resulting in the number of knocking cycles increases with the increase of knocking intensity. Second, additional experiments were conducted under ultra-lean conditions in the λ = 1.82–1.97 range since the effects of multiple spark discharge on SI combustion are much more pronounced for the leaner operation. The results show that the net indicated thermal efficiency increases quite linearly with increasing λ for all multiple spark discharges considered. Especially, for the multiple spark discharge of Δt_i = 0.2 ms, a proper spark discharge energy is generated from the spark timing to a certain timing after the first start of spark discharge, which advances both the spark timing and the initial combustion phase. A combination of the advanced spark timing and the advanced initial combustion phase leads to the advancement of main combustion phase, and eventually shorten the combustion duration. Because of shortened combustion duration, stable ultra-lean operation at around λ = 1.94 can be achieved with the highest net indicated thermal efficiency of 47.0%.

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Nomenclature

ATDC	after top dead center
COV of $IMEP_n$	coefficient of variation of $IMEP_n$
CMC	coupled multi-charge ignition
DI	direct injection
DCO	dual coil offset
KI	knock intensity
MBT	minimum advance for best torque
MSI	multi spark ignition
$IMEP_n$	net indicated mean effective pressure
SI	spark ignition
ST	spark timing
TCI	transistor coil ignition
TPS	transient plasma system
λ	excess-air ratio
P_c	in-cylinder gas pressure
η_{ith}	net indicated thermal efficiency
R^2	coefficient of determination
θ	crank angle
θ_5	CA5 (5% burn point)
θ_{10}	CA10 (10% burn point)
θ_{50}	CA50 (50% burn point)
θ_{90}	CA90 (90% burn point)
θ_{ST}	ST
$\Delta\theta_{ST\text{-}5}$	ST-to-CA5 duration
$\Delta\theta_{10\text{-}90}$	CA10-to-CA90 duration
Q_{hr}	heat release
$dQ_{hr}/d\theta$	heat-release rate
Q_{hr}	integrated heat release
ΣQ_{hr}	total heat release
ST-to-CA5	duration from spark timing to CA5
CA10-to-CA90	duration from CA10 to CA90
I_1	primary current
I_d	discharge current
V_d	discharge voltage
E_d	discharge energy
dE_d/dt or $dE_d/d\theta$	discharge energy release rate
E_d	integrated discharge energy
ΣE_d	total discharge energy
t	time
t_d	total discharge duration
Δt_i	time interval between spark discharges

1. Introduction

Gasoline spark ignition (SI) engines are the dominant form of power units for light-to-medium load passenger cars [1]. Because of its widespread use, SI engines have been developed for many decades to improve the thermal efficiency [2–6]. However, due to lower thermal efficiency of stoichiometric operation which is the dominating combustion mode for SI engines, SI engines suffer from meeting stringent regulations on fuel economy and CO_2 emissions [7–9]. There are several reasons why stoichiometric operation limits the observed thermal efficiency, especially for low and intermediate loads, even though it allows the application of a three-way catalyst for cost-effective reduction of nitrogen oxides (NO_x) and oxidation of carbon monoxide (CO) and hydrocarbon (HC) [10]. First, the required intake throttling results in significant pumping losses [11–13]. Second, high combustion temperatures lead to both high heat-transfer losses [14,15] and unfavorable thermodynamic properties of the combustion products. The latter manifests itself as high specific heat capacity, reducing both the ratio of specific heats and the work-extraction efficiency of the expansion stroke [16]. A third factor is the inability of the stoichiometric combustion to fully complete near TDC due to dissociation of CO_2 in the hot O_2-depleted gases [10,17].

Lean operation can improve the thermal efficiency of SI engines by mitigating all of these limitations of stoichiometric operation [18,19]. Furthermore, the beneficial effects of lean operation on the thermal efficiency are much more pronounced for the leaner operation [20]. However, the cycle-to-cycle variations of SI combustion increase with increasing excess-air ratio (λ) because of a reduction of flame speeds [21,22]. The flame speeds during and shortly after the spark discharge are expected to be substantially lower for the leaner operation, and therefore the flame speed becomes too low to ensure robust flame development as the in-cylinder charge is leaned out. The lower flame speed for the leaner operation eventually becomes a particular problem from the perspective of ignition and flame spread throughout the in-cylinder charge [23,24]. To ensure stable, complete and fast combustion, successful inflammation is critically important first, which refers to creating a flame kernel that survives its nascent laminar state and transitions into fully developed turbulent deflagration [19]. For successful inflammation, the time scale for inflammation (inflammation time) is an important factor that significantly influences on both the combustion phasing and the combustion duration. Usually, for quantitative comparisons, the inflammation time is equated to a duration from the spark timing (ST) to the 5% burn point (CA5). Furthermore, the combustion duration is equated to a duration from the 10% burn point (CA10) to the 90% burn point (CA90). With the earlier of spark timing for the leaner operation to maintain the targeted combustion phasing, the inflammation time from ST to CA5 (ST-to-CA5 duration) becomes longer by the compounding effects of lower laminar flame speed at higher excess-air ratio (λ), and the lower compressed-gas temperature at earlier crank angles. This very slow inflammation resulted from the longer ST-to-CA5 duration leads to excessive combustion-phasing retard despite the more advanced spark timing, and then the combustion is occurred much later into the expansion stroke. Since the volume expansion of the in-cylinder charge by piston motion increases during the expansion stroke, the greater volume and volume-expansion rate with combustion-phasing retard more strongly counteracts the temperature rise. This causes unfavorably long combustion duration from CA10 to CA90 (CA10-to-CA90 duration) with the increase of cycle-to-cycle variations. Finally, the combustion efficiency drops off quickly due to unacceptable cycle-to-cycle variations of SI combustion with the appearance of partial-burn and misfire cycles, resulting in the observed drop in the thermal efficiency. Ultimately, the causes of these combustion fluctuations can largely be attributed to the cycle-to-cycle variations of the fragile early flame kernel.

One effective way to shorten the inflammation time for successful inflammation under lean conditions is to produce robust and multiple flame kernels by effective ignition. To provide effective ignition for lean operations, a variety of advanced ignition systems have been developed [25–27]. In particular, for extending the lean-stability limit and the EGR tolerance of SI engines, the development efforts of the ignition system have tended to focus on the multi spark ignition system for implementing multiple spark discharge by adjusting the number of spark discharges and the time interval between spark discharges [28,29]. (The term "multiple spark discharge" refers to the charging and discharging multiple times during a single combustion event.) However, there are no systematic experiments to explain why the lean-stability limit are extended by the multiple spark discharge, although the application of the multiple spark discharge to SI engines is a beneficial way to extend the lean-stability limit. Because of this, this study first investigates the relationship between the spark discharge energy and the combustion phasing of lean SI operation for clarifying the reasons on the extension of lean-stability limit by the multiple spark