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On the sensitivity of low temperature combustion to spark assist near flame limit conditions

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HIGHLIGHTS

- The effect of spark assist on air and EGR dilute HCCI combustion was examined.
- Spark had greater combustion advance effect on more air dilute (vs. EGR dilute) mixtures.
- Combustion advance was caused by an increased fraction of flame-based heat release.
- Flame quenching likely affected mixtures that showed a non-response to spark assist.

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ABSTRACT

Spark assisted compression ignition (SACI) is a practical mode for controlling the heat release rate of low temperature combustion (LTC). While flames are key phenomena in the SACI combustion process, they may not always be effective or viable under the mildly stratified and highly dilute low burned gas temperature conditions of LTC. To better understand the limits of flammability or flame effectiveness, this work explores combustion within a single cylinder direct injection engine near the high load limit of the HCCI combustion regime, where spark induced flame propagation has been seen to affect combustion phasing and heat release rate. Flame limiting conditions were identified using progressively more advanced spark timing, up to 120° before top dead center, for differing levels of air and EGR dilution while holding the chemical energy content of the charge constant. Under air dilute conditions, the measured combustion phasing advanced from 8° to 0° after top dead center with spark advance, while almost no effect was seen under EGR dilute conditions. Estimates of the experimental global and local state conditions were made at the time of spark using heat release analysis and a KIVA-3V engine model, respectively, and the flammability for each case was evaluated using the Karlovitz criterion. The results show that fuel rich stratification near the spark plug was likely responsible for the observed variations in the SACI flame behavior.

1. Introduction

Spark assisted compression ignition (SACI) has been demonstrated as a method to control the phasing, burn rate, and stability of a primarily auto-igniting fuel/air charge [1,2]. Optical engine studies of SACI suggest the spark event initiates flame propagation within a highly dilute mixture, accelerating the auto-ignition of the surrounding unburned charge via compression heating [3–5]. The spark provides a crucial parameter for control during transient mode switches between homogeneous charge compression ignition (HCCI), SACI, and spark ignited (SI) combustion, which may be necessary to implement low temperature combustion (LTC) in practical engines [6,7]. Understanding the effectiveness of dilute SACI flames and their ability to control combustion phasing at a given operating condition is critical for avoiding periods of excessive pressure rise rates or instability and misfire.

While experience has shown that gasoline fueled spark ignited engines encounter a lean limit at approximately 30% dilution by mass [8], it is possible to sustain flames under higher levels of dilution provided the unburned gas temperature (T_u) is in the vicinity of the auto-ignition temperature and the energy content of the

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Nomenclature

AKI	anti-knock index
aTDC	after top dead center
bTDC	before top dead center
CA	crank angle
CA50	combustion phasing; crank angle where 50% of fuel mass is burned
CoV	coefficient of variation
δ	laminar flame thickness
EGR	exhaust gas recirculation
HCCI	homogeneous charge compression ignition
HR	heat release
$IMEP_n$	net indicated mean effective pressure
L	turbulent integral length scale
LTC	low temperature combustion
Ka	Karlovitz number
MBT	maximum brake torque
NVO	negative valve overlap
ϕ	fuel-to-air equivalence ratio
ϕ'	fuel-to-charge equivalence ratio
rms	root mean square
σ	standard deviation
SACI	spark assisted compression ignition
SI	spark ignited
S_L	laminar flame speed
T_b	burned gas temperature
TDC	top dead center
T_u	unburned gas temperature
τ_{ID}	ignition delay time
τ_F	flame time
u'	rms turbulent velocity

charge is sufficiently high [9]. For a given spark timing, as T_u increases conditions become more favorable for auto-ignition and flame propagation tends to become an increasingly smaller percentage of the overall heat release [2]. In practical SACI engines, T_u and dilution level are controlled by valve timing strategies that retain large quantities of high temperature residual gas, which can range from 30% to 60% of the total charge mass, depending on engine load [2].

Due to high levels of charge dilution, SACI flames have reduced burned gas temperatures (T_b) relative to undilute stoichiometric flames typical of SI engines [9]. Laminar flame simulations have predicted that premixed flames can be sustained under ultra-dilute conditions provided that T_b exceeds ~1450–1500 K [10–13]; otherwise, flame quenching can be induced by processes such as turbulent strain or external heat loss [14–17]. It has been proposed based upon dimensional analysis that when the flame thickness exceeds the smallest scales of the turbulent flow, transport rates within the flame are increased, broadening it to the point where there is a sharp drop in temperature that leads to flame extinction. This limit is known as the Klimov–Williams criterion [18]. However, the existence of such behavior has not been directly confirmed; rather, flames have been observed to remain viable even when the flame thickness is many times that of the smallest scale of the turbulent flow, both experimentally and in direct simulation [16,17,19].

Several fundamental experiments have examined turbulent flame quenching. Abdel-Gayed et al. [20] compared schlieren images of turbulent flames from fan stirred bombs over a broad range of turbulent intensities and equivalence ratios for both hydrocarbon and hydrogen fuels to define the regimes of turbulent flame propagation. Flame appearance and quenching were well correlated to the Karlovitz (Ka) and Lewis numbers. Roberts et al. [17] used a laminar toroidal vortex to quench laminar premixed methane flames with a fuel-to-air equivalence ratio (ϕ) equal to 0.55. The maximum temperature of the product gases for the unperturbed laminar flames was 1525 K; quenching was observed to occur when the product gas temperatures cooled to ~1300 K. Quenching vortex Karlovitz numbers (~4.5–14) were similar to the two-dimensional direct numerical simulations of Poinsot et al. [16]. Roberts et al. [17] also found the quenching Ka for propane–air flames differed from that of methane–air flames, indicating the importance of detailed chemistry and transport properties to the quenching process.

Additional studies have investigated flame quenching in SI engines. Quader [8] performed experiments in a single cylinder engine with adjustable compression ratio to understand if flame initiation and/or flame propagation limited lean SI operation. In the experiments, spark timing was advanced earlier into compression and away from maximum brake torque (MBT) timing to define the ignition limit where the onset of misfire occurred. Additionally, the partial burn/flame propagation limit was found by retarding spark timing from MBT until incomplete flame propagation, as determined by the lack of an ionization signal near the cylinder wall, occurred in at least 2–4% of the cycles. As the mixture was leaned, the two limits converged at the MBT lean misfire limit ($\phi = 0.65$), indicating that both ignition and flame propagation constrain highly dilute operation. Peterson et al. [21] used high-speed fuel fluorescence and particle image velocimetry measurements combined with spark discharge measurements to identify the cause of misfire and partial burn cycles in a stratified spark ignited direct injection engine. The results of the study showed abnormal spark behavior was not the cause of misfire, as all cycles had sufficient electrical spark energy to ignite the mixture near the spark plug. For the cycles that misfired, it was shown that a flame kernel developed but failed to propagate due to the highly lean/dilute mixtures surrounding the flame kernel.

While simple models exist for the prediction of misfire, these models have not been validated under the highly dilute conditions typical of SACI/LTC. Dai et al. [15] validated a misfire model for SI combustion based on the flame quench correlations reported in the Leeds diagram of Abdel-Gayed et al. [20]. The model was implemented into a cycle simulation, which in turn determined the parameters necessary for the misfire model. With the misfire model, the cycle simulation was capable of predicting corresponding experimental misfire limits (defined when at least 0.5–1% of the total cycles misfired) for two engine designs using a variety of equivalence ratios, exhaust gas recirculation (EGR) rates, spark timings, and speeds and loads. For this definition of misfire, the experimental misfire limit closely matched the quenching limit of the Leeds diagram based on model predictions of turbulent flow and laminar flame characteristics at the time of spark. Dai et al. [15] predicted that this result would likely be applicable to most SI engines.

A variety of diluents can be used with LTC, and it is well known that dilution method impacts the combustion process. Dilution with EGR as opposed to air has been studied extensively in HCCI and SI combustion, including the effects on ignition delay time and laminar flame speed. Dec et al. [22] and Olsson et al. [23] showed that the use of EGR as opposed to air dilution reduced peak rates of heat release and increased combustion duration for HCCI