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The effect of spark timing and negative valve overlap on Spark Assisted Compression Ignition combustion heat release rate

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Abstract

Spark Assisted Compression Ignition (SACI) combustion is capable of partially decoupling combustion phasing from peak heat release rate, overcoming one of the major challenges associated with low temperature combustion. Experimental SACI studies have shown that for a given combustion phasing, peak heat release rate can be modulated by trading the fraction of the fresh charge consumed by flame propagation with the fraction consumed by auto-ignition. The chemical and physical mechanisms controlling the changes in heat release rate are not well known. The current work uses computational simulation to explore these modes through the combined control of spark timing and charge temperature via changes in negative valve overlap. Open cycle CFD simulation results are compared with experimental data to validate a newly developed SACI model, and used to gain insight into the processes governing combustion behavior. The simulations predict a 43% reduction in the peak rate of heat release with increasing spark advance, while the unburned charge mass at the time of auto-ignition decreases by only 23%. Detailed analysis of the end-gas thermodynamic state prior to auto-ignition shows as spark is advanced, the end-gas thermal and compositional distributions vary with the fraction of the charge consumed by the flame. The reduction in the rate of peak rate of heat release during the auto-ignition process is therefore a function of both the mass of the end-gas and the end-gas reactivity.

Keywords: Low temperature combustion; Spark Assisted Compression Ignition; Computational Fluid Dynamics; Combustion modes; Flamelet and Auto-ignition Modeling

1. Introduction

High thermal efficiency with low emissions has been successfully demonstrated using homogeneous charge compression ignition (HCCI)

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combustion [1–3]. However, it is difficult to decouple HCCI combustion phasing from peak rate of heat release [4]. High rates of heat release determine the high load limit for HCCI, which limits the use of HCCI to low load regimes [5–7]. These challenges have generated interest in alternative low temperature combustion modes such as Spark Assisted Compression Ignition (SACI) which expand the high load limit beyond the HCCI regime. Optical engine studies of SACI combustion have shown key features to be the presence of turbulent flames initiated at the spark plug, followed by end gas auto-ignition [8]. Laminar flame modeling predicts that flames can exist under the highly dilute conditions typical of SACI operation, provided that the unburned gas temperature is sufficiently high [9].

Recent experimental work has shown that the heat release rate of SACI combustion can be varied by controlling the relative contributions of the flame and auto-ignition combustion modes at constant combustion phasing [10,11], where phasing is defined as crank angle of 50% mass fraction burned (CA50). To adjust the balance between modes, the temperature at intake valve closing (T_{IVC}) and spark timing were adjusted simultaneously. For a given combustion phasing, a higher T_{IVC} required less spark advance (and associated flame compression of the end-gas) to achieve the end-gas temperature required for auto-ignition. Using this strategy the peak heat release rate was reduced by 40% with a 75% reduction in ringing intensity and 20% reduction in estimated end-gas mass at autoignition, while maintaining thermal efficiency. While these studies demonstrated the potential of such strategies, the mechanism(s) affecting the peak heat release rates have not be identified or quantified. Such information will enable the development of SACI strategies to achieve a wider engine operating regime.

The primary objective of the present investigation was to better identify the physical processes governing the behavior of SACI combustion at constant phasing as the fraction of flame and auto-ignition heat release are varied. The 3D reacting CFD code KIVA-3V was used to replicate the experimentally observed behavior of decreasing peak heat release rates with simultaneously increasing spark advance and decreasing T_{IVC}. Detailed analysis of the simulated end-gas states was performed to identify the factors responsible for the changes in the overall heat release rate.

2. Model formulation and configuration

The modeling work conducted here is designed to understand the physical processes responsible for the experimental SACI behavior previously reported in detail by Olesky et al. [10]. In that study T_{IVC} and spark timing were simultaneously varied to maintain combustion phasing while manipulating the peak rate of heat release. Experiments were conducted in a single cylinder research engine unthrottled at atmospheric pressure, with constant fuel injection of 19 mg/stroke resulting in ≈6.5 bar $IMEP_n$ and ≈42% net thermal efficiency. Model parameters and inputs are configured to match the experiment wherever possible, with engine geometry provided in Table 1 and operating conditions in Table 2.

Simulations of SACI combustion were conducted using the 3D CFD code KIVA-3V [12]. Turbulent flame propagation was simulated using the Coherent Flamelet model (CF) [13,14], while detailed chemistry was simulated using the fully coupled Multi-Zone approach (MZ) [15]. A detailed description of the complete CFMZ model formulation is provided elsewhere [16,17].

The CFMZ model is designed for use with detailed chemistry, solving two transport equations for every species in the chemical mechanism, one for the average composition of the cell and one for the unburned gas composition. Using this approach the end-gas mass consumed by the flame is modeled separately from the heat release associated with chemically controlled combustion. In each cell, fuel mass can be consumed entirely through flame propagation, auto-ignition, or a combination of the two modes, allowing the model to capture combustion in the HCCI, SACI, and SI combustion regimes.

The chemical mechanism used for end- and burned-gas chemistry in this work was the skeletal 215 species isooctane mechanism of Tham et al. [18], derived from the detailed mechanism of Curran et al. [19]. The spark event and flame kernel was tracked by lagrangian particles following the approach of Tan and Reitz [20], with the transition from purely laminar propagation to a laminar-turbulent phase and fully turbulent flame propagation modeled using the method of Boudier et al. [21]. A transport equation for the flame surface density Σ, the flame surface area per unit cell volume, was used to predict the surface area of the flame front [14]. Turbulent flame stretch was captured with a source term in the Σ transport equation from the phenomenological Intermittent Turbulence Net Flame Stretch (ITNFS) model of Meneveau and Poinsot [13], which uses characteristic velocity

Table 1
Engine and mesh geometry.

Parameter	Value	Unit
Displacement	550	cm^3
Bore	86.0	mm
Stroke	94.6	mm
Con. rod length	156.5	mm
Compression ratio	12.4:1	

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