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Enhanced heat release analysis for advanced multi-mode combustion engine experiments

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HIGHLIGHTS

- Developed analytical methods to characterize advanced multi-mode combustion.
- Integrated methods into Advanced Combustion Engine Heat Release Analysis (ACE-HRA).
- ACE-HRA was assessed by comparison with high fidelity SACI engine simulations.
- Quantified the sensitivity of ACE-HRA estimates to key experimental input data.
- ACE-HRA used to infer physical behavior in representative SACI engine experiments.

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ABSTRACT

Advanced combustion strategies, such as Homogeneous-Charge Compression-Ignition (HCCI) and Spark-Assisted HCCI or Spark-Assisted Compression-Ignition (SACI) hold considerable promise for improving engine efficiencies while maintaining low pollutant emissions, yet few models exist that accurately include the important chemical and physical mechanisms of these advanced combustion strategies. Further, experimental data from advanced combustion engine experiments are not well represented using conventional spark ignited analytical tools. This paper presents new methods for advanced combustion analysis that integrate previous analytical methods with new algorithms to capture the unique features of advanced combustion strategies like SACI.

The new analytical capabilities were incorporated into a program which was designated the Advanced Combustion Engine Heat Release Analysis (ACE-HRA) tool. The models developed and applied in ACE-HRA were assessed by comparison with high fidelity engine simulations of HCCI and SACI. The high fidelity simulations provided data sets with detailed predictions of heat release rates, temperatures, auto-ignition timing, flame speeds and other key parameters not resolved or measured in engine experiments. The sensitivity of ACE-HRA estimates to model input data was quantified for important engine performance parameters. The sensitivity analysis showed that estimates for in-cylinder masses have the largest overall impact on the ACE-HRA results (e.g. ±10% variation led to changes on the order of ±5–10% in peak rate of heat release, burn duration and peak temperature). Noticeable differences in peak heat release rate and ringing intensity were also observed when comparing cycle-by-cycle analysis against ensemble-average analysis, which has implications on how the results are interpreted and applied in modeling work.

After validating ACE-HRA with the high-fidelity simulations, ACE-HRA was applied to interpret the data from a recent experimental study of SACI combustion. The ACE-HRA methods were used to infer the effects of flame propagation on in-cylinder gradients and cycle-to-cycle variability, and to provide quantitative estimates for the associated changes in the end-gas burn rate. The trends observed, such as the decrease in burn rate for later auto-ignition and higher burn fraction by flame, provide more in-depth understanding of SACI combustion and demonstrate the insight that can be revealed by the new ACE-HRA tool.

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Nomenclature

Abbreviations

A/BTC	after/before top dead center
ACE	advanced combustion engine
AI	auto-ignition
BC	bottom dead center
CA	crank-angle
CFD	computational fluid dynamics
CFM	coherent flamelet model
COV	coefficient of variability
CR	compression ratio
EG	end-gas
EGR	exhaust gas recirculation
EOC	end of combustion
EVC	exhaust valve closing
EVO	exhaust valve opening
FFVA	fully-flexible valve actuation
HCCI	homogeneous charge compression ignition
HR	heat release
HT	heat transfer
IMEP	indicated mean effective pressure
IMPR	intake manifold pressure referencing
IVC	intake valve closing
IVO	intake valve opening
MMC	multi-mode combustion
MZ	multi-zone
NTC	negative temperature coefficient
NVO	negative valve overlap
PIPR	polytropic index pressure referencing
R.I.	ringing intensity
RGF	residual gas fraction
RoHR	rate of heat release
SA	spark advance
SACI	spark-assisted compression ignition
SI	spark ignition
SOC	start of combustion
TC	top dead center

Definitions

α_{HT}	heat transfer energy closure factor
γ	specific heat ratio
η_{comb}	combustion efficiency
θ	crank-angle
κ	curvature
Φ	fuel/air equivalence ratio
c_v	specific heat at constant volume
h	specific enthalpy
h^{HT}	convection heat transfer coefficient
m	mass
m^k	mass of species k
t	time
x_b	burn fraction
A	combustion chamber surface area
B	cylinder bore
$CA(X)$	crank-angle at X% burn (e.g. CA50)
$EG(X)$	crank-angle at X% EG burn (e.g. EG50)
H	total enthalpy
L	characteristic heat transfer length
P	pressure
Q^{HR}	heat release
Q^{HT}	heat transfer
Q_{LHV}	lower heating value
R	gas constant
S_L	laminar flame speed
$\overline{S_p}$	mean piston speed
T	temperature
U	total internal energy
V	combustion chamber volume
Y^k	mass fraction of species k

Subscripts/superscripts

air	air-related quantity
b	post-flame zone
cyl	in-cylinder quantity
d	displacement
e-EGR	external EGR
exh	exhaust-based quantity
fuel	fuel-related quantity
i-EGR	internal EGR
peak/max	peak or maximum value
prod	combustion products
r	reference value
reac	unburned reactants
tot	total-based quantity
u	end-gas zone
AI	end-gas auto-ignition quantity
EG	end-gas quantity
FL	flame-based quantity
IGN	value at auto-ignition timing
SPK	value at spark timing

1. Introduction

Advanced combustion strategies, such as Homogeneous-Charge Compression-Ignition (HCCI) and Spark-Assisted HCCI (SA-HCCI) or Spark-Assisted Compression-Ignition (SACI), are important methods to improve internal combustion engine efficiency and emissions. HCCI combustion relies on chemically controlled auto-ignition [1–4], and can be operated with much leaner mixtures, higher compression ratios and un-throttled, considerably increasing thermodynamic efficiency compared to conventional spark-ignition (SI). However, the HCCI operating range is limited by high pressure-rise rates due to rapid combustion events, and stability issues resulting from the lack of a direct ignition trigger. SA-HCCI or SACI is a two-stage, hybrid advanced combustion mode, which uses spark-ignition and flame propagation to directly initiate or stimulate the occurrence of auto-ignition and HCCI-like combustion [5–7]. SACI allows for combustion under conditions not possible when exclusively using SI or HCCI. SACI can also be used to reduce peak heat release rates. Experimental studies have confirmed the viability of SACI and have suggested potential operating strategies (e.g. [8,9]). Conceptual studies have also demonstrated that sizable vehicle fuel economy gains, between 23% and 58%, are achievable if SACI can be effectively implemented [10].

Optimization of HCCI and SACI methods requires improved understanding of the important combustion processes. Heat release analysis is an essential tool for interpreting experimental pressure data from HCCI, SACI and conventional spark ignition (SI) strategies, and heat release analysis of experimental data provides key inputs for model development and validation. Heat release analysis typically follows a regressive modeling approach, where the measured in-cylinder pressure, combustion efficiency and estimated trapped masses are used to calculate the mean gas temperature, composition, and combustion heat release.