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Evaluating temperature and fuel stratification for heat-release rate control in a reactivity-controlled compression-ignition engine using optical diagnostics and chemical kinetics modeling

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ABSTRACT

The combustion process in a dual-fuel, reactivity-controlled compression-ignition (RCCI) engine is investigated using a combination of optical diagnostics and chemical kinetics modeling to explain the role of equivalence ratio, temperature, and fuel reactivity stratification for heat-release rate control. An optically accessible engine is operated in the RCCI combustion mode using gasoline primary reference fuels (PRF). A well-mixed charge of iso-octane (PRF = 100) is created by injecting fuel into the engine cylinder during the intake stroke using a gasoline-type direct injector. Later in the cycle, n-heptane (PRF = 0) is delivered through a centrally mounted diesel-type common-rail injector. This injection strategy generates stratification in equivalence ratio, fuel blend, and temperature. The first part of this study uses a high-speed camera to image the injection events and record high-temperature combustion chemiluminescence. The chemiluminescence imaging showed that, at the operating condition studied in the present work, mixtures in the squish region ignite first, and the reaction zone proceeds inward toward the center of the combustion chamber. The second part of this study investigates the charge preparation of the RCCI strategy using planar laser-induced fluorescence (PLIF) of a fuel tracer under non-reacting conditions to quantify fuel concentration distributions prior to ignition. The fuel-tracer PLIF data show that the combustion event proceeds down gradients in the n-heptane distribution. The third part of the study uses chemical kinetics modeling over a range of mixtures spanning the distributions observed from the fuel-tracer fluorescence imaging to isolate the roles of temperature, equivalence ratio, and PRF number stratification. The simulations predict that PRF number stratification is the dominant factor controlling the ignition location and growth rate of the reaction zone. Equivalence ratio has a smaller, but still significant, influence. Temperature stratification had a negligible influence due to the NTC behavior of the PRF mixtures.

1. Introduction

Highly premixed compression ignition (PCI) strategies, e.g., homogenous charge compression ignition (HCCI), offer attractive emissions and performance characteristics (i.e., high efficiency and low NOx and soot emissions) [1,2,3,4]. Although promising, these operating strategies are generally confined to low engine loads due to difficulties controlling the heat-release rate and lack of an adequate combustion phasing control mechanism. Recently, Sjoberg and Dec [5] proposed that partial fuel-stratification may be a promising method to control the heat-release rate for HCCI engines. Additionally, Dec et al. [6,7] showed that harnessing natural thermal stratification is a potential method to control HCCI heat-release rates and increase the HCCI operating range. Both thermal and equivalence ratio stratification introduce non-uniformities in the auto-ignition characteristics of the charge. These non-uniformities result in a staged ignition event, which tends to reduce the peak heat-release rate.

Kokjohn et al. [8] proposed blending two fuels with different auto-ignition characteristics inside the combustion chamber to artificially generate non-uniformities in the auto-ignition characteristics of the charge. Using metal engine experiments, Hanson et al. [9] and Kokjohn et al. [10] showed that compared to single-fuel strategies, stratifying the fuel reactivity via in-cylinder blending of two fuels of differing reactivity improves the control over the

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Definition of Acronyms

AHRR	Apparent heat release rate
ATDC	After top dead center
BDC	Bottom dead center
CCD	Charge coupled device
CFD	Computational fluid dynamics
CMOS	Complementary metal oxide semiconductor
CR	Common-rail
DI	Direct injected
DOE	Design of Experiments
FOV	Field of View
FTIR	Fourier-transform infrared
GDI	Gasoline direct injection
HCCI	Homogeneous charge compression ignition
HPLC	High performance liquid chromatography
HSC	High speed camera
IMEP	Indicated mean effective pressure
IR	Infrared
LIF	Laser induced fluorescence
LWP	Long wave pass
NTC	Negative Temperature Coefficient
PCI	Premixed compression ignition
PLIF	Planar laser-induced fluorescence
PRF	Primary reference fuel
RCCI	Reactivity controlled compression ignition
ROI	Rate of Injection
SNR	Signal-to-noise ratio
SOI	Start of Injection
SWP	Short wave pass
TDC	Top dead center
UV	Ultra violet

heat-release rate and thereby allows extension of PCI combustion to higher engine loads. Consequently, they termed this alternative combustion mode "reactivity controlled compression ignition," or RCCI. Further, the metal engine experiments have shown that RCCI combustion can achieve gross indicated efficiencies over 50 percent for a wide range of operating conditions while meeting current, heavy-duty, on-highway NOx and soot emissions limits without exhaust-gas aftertreatment.[1] The high efficiency, compared to conventional diesel combustion, is primarily due to reductions in heat transfer losses by avoiding high-temperature regions [11]. Although these metal engine experiments are useful to understand emissions and performance tradeoffs, they do not reveal details of the dominant in-cylinder processes controlling RCCI combustion.

In an attempt to improve the fundamental understanding of RCCI combustion, Splitter et al. [12] used in-cylinder Fourier-transform infrared (FTIR) spectroscopy to investigate the evolution of the RCCI combustion process. FTIR spectra were acquired at two locations, to provide a degree of spatial resolution, and were indexed to engine crank-angle to give cycle-averaged, crank-angle-resolved in-cylinder spectroscopy. Their results suggested that the RCCI combustion process proceeded at different rates in different locations of the cylinder. However, their measurements were restricted by the limited optical access of their engine. Additionally, several studies have used detailed CFD modeling (e.g., [8]) with reduced kinetics mechanisms to investigate RCCI combustion. The CFD modeling predicted that non-uniformities in the auto-ignition characteristics of the charge (i.e., fuel reactivity), as created by in-cylinder fuel blending, control the heat-release rate.

In the present study, RCCI combustion is investigated in a heavy-duty, single cylinder, optically accessible research engine using a combination of high-speed chemiluminescence imaging and fuel-tracer planar laser-induced fluorescence (PLIF). There are three main objectives. The first objective is to gain insight into the dominant mixing and ignition processes controlling the RCCI combustion event through observation of ignition locations and key features of the reaction zone growth. The second is to evaluate the dependence of the reaction-zone growth on fuel reactivity stratification. The third objective is to isolate the roles of temperature, equivalence ratio, and fuel blend stratification.

[1] Note that a diesel oxidation catalyst would still be required to control relatively high hydrocarbon and carbon monoxide emissions.

2. Experimental setup

2.1. Engine specifications

The single-cylinder, direct-injection, 4-stroke optically accessible research engine of this study is based on a Cummins N14 production diesel engine. Table 1 gives the engine specifications and Fig. 1 shows a schematic of the combustion chamber. The research engine is typical of a heavy-duty diesel engine with a 13.97 cm bore and 15.24 cm stroke giving a displacement of 2.34 L per cylinder. The intake port geometry of the production engine, which has a steady state (i.e., measured on a flow-bench) swirl ratio of 0.5 [13], is preserved in the research engine. To allow optical access, the engine is equipped with an extended piston and the stock metal piston bowl has been replaced with a flat fused silica piston crown window. Further, one of the two exhaust valves has been replaced with a window, and a periscope mirror in the rocker box provides a view through that window of a portion of the squish region (i.e., the region above the piston bowl-rim). Four windows are also located around the upper portion of the cylinder wall to allow cross-optical access for laser-based diagnostics. A complete description of the engine development is available in Ref. [14].

2.1.1. Fuel injection systems

RCCI combustion is achieved by using in-cylinder blending of two fuels with different reactivities (i.e., auto-ignition

Table 1
Sandia heavy-duty optical engine specifications.

Engine base type	Cummins N-14, DI diesel
Number of cylinders	1
Cycle	4-stroke
Number of intake valves	2
Number of exhaust valves	1[a]
Combustion chamber	Quiescent, flat bowl
Swirl Ratio	0.5 (approximate)
Bore	13.97 cm
Stroke	15.24 cm
Bowl width	9.78 cm
Displacement	2.34 liters
Connecting rod length	30.48 cm
Piston pin offset	None
Geometric compression ratio	10.75:1

[a] One of the two exhaust valves of the production cylinder head has been replaced by a window and periscope.