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Co-Optima Project E2.2.2: Accelerate Development of ACI/LTC, Fuel Effects on RCCI Combustion

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Project Introduction

Many advanced combustion approaches have demonstrated potential for achieving diesel-like thermal efficiency but with much lower pollutant emissions of particulate matter (PM) and nitrogen oxides (NOx). RCCI is one advanced combustion concept, which makes use of in-cylinder blending of two fuels with differing reactivity for improved control of the combustion phasing and rate (Reitz et al., 2015). Previous research and development at ORNL has demonstrated successful implementation of RCCI on a light-duty multi-cylinder engine over a wide range of operating conditions (Curran et al., 2015). Several challenges were encountered when extending the research to practical applications, including limits to the operating range, both for high and low loads.

Co-optimizing the engine and fuel aspects of the RCCI approach might allow these operating limits to be overcome. The in-cylinder mechanisms by which fuel properties interact with engine operating condition variables is not well understood, however, in part because RCCI is a new combustion concept that is still being developed, and limited data have been acquired to date, especially using in-cylinder optical/imaging diagnostics. The objective of this work is to use in-cylinder diagnostics in a heavy-duty single-cylinder optical engine at SNL to understand the interplay between fuel properties and engine hardware and operating conditions for RCCI in general, and in particular for the light-duty multi-cylinder all-metal RCCI engine experiments at ORNL.

Objectives

Overall Objectives

- Measure in-cylinder mixing/ kinetics to optimize dual-fuel heat-release for noise, efficiency, and load range
- Understand mixing/ignition interaction for different fuel reactivity combinations
- Support metal-engine reactivity-controlled compression-ignition (RCCI) E.2.2.1 task work at Oak Ridge National Laboratory (ORNL)

Fiscal Year (FY) 2017 Objectives

- Identify/demonstrate problematic low-load operating conditions from multi-cylinder all-metal engine experiments at ORNL
- Scope in-cylinder behavior using chemiluminescence imaging to guide application follow-on quantitative laser diagnostics

- Use fuel-tracer/combustion-intermediate fluorescence to quantify coupling of fuel properties with physical processes

Approach

This project uses an optically-accessible, heavy-duty, direct-injection diesel engine (Figure 1). To achieve dual-fueling for RCCI, a Bosch gasoline direct injector (GDI) operating with iso-octane at a fuel pressure of 100 bar was added in place of one of the five cylinder-wall windows (see Figure 1). For diesel-type fuels, the engine retains a centrally-located light-duty common-rail (CR) injector operating with n-heptane at a rail pressure of 800 bar. A large window in the piston crown provides primary imaging access to the piston bowl, and other windows at the cylinder wall provide cross-optical access for laser diagnostics or imaging.

The optical engine experiment shown in Figure 1 uses two cameras for simultaneous imaging of in-cylinder infrared (IR) and visible natural luminosity (NL) emissions. The beamsplitter transmits IR emission to an IR camera that records one image per cycle at an exposure of 130 microseconds. The camera is equipped with a bandpass filter centered at 3.3 microns with a passband of 430 nm, which was chosen to isolate emission from hot fuel vapors. After ignition, the camera also records emission from other combustion-generated sources. The visible NL emission is reflected off the beamsplitter and is directed to a high-speed complementary metal oxide semiconductor (CMOS) camera with an exposure of 130 microseconds and a rate of 7200 frames per second (1 image per crank angle degree).

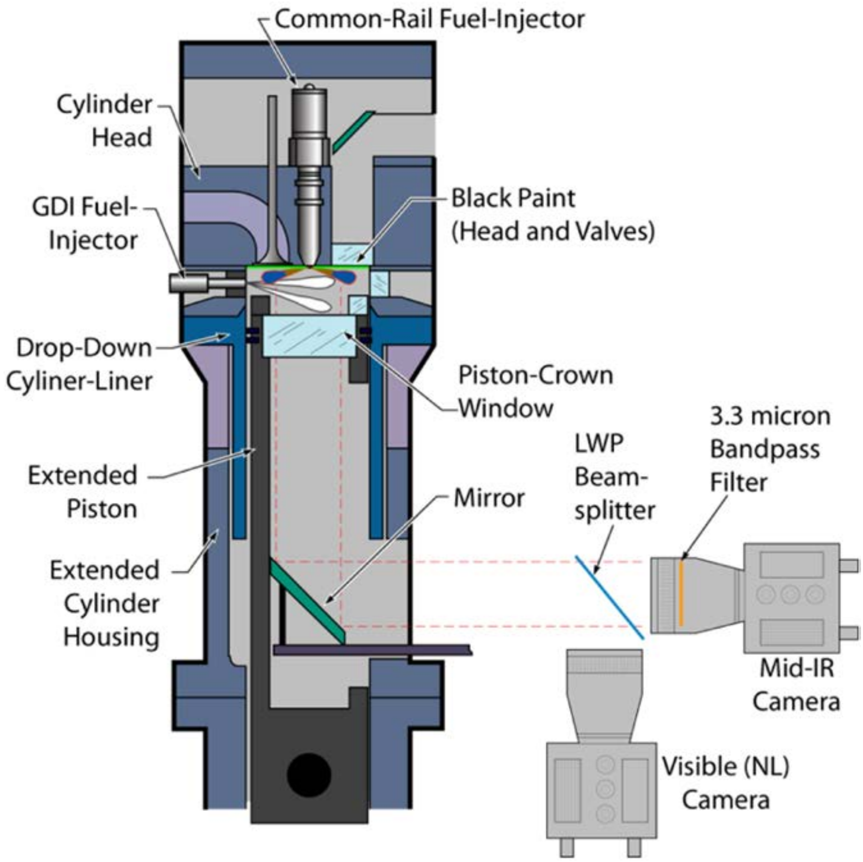

Figure 1. Schematic diagram of the heavy-duty single-cylinder optical diesel engine and optical setup with IR emission and visible natural combustion luminosity cameras.

Results

Figure 2 shows the combustion phasing, represented by the crank-angle timing at 50% mass-fraction burned (CA50), for a timing sweep of the CR injection in the SNL heavy-duty single-cylinder optical engine and the

ORNL light-duty multi-cylinder all-metal engine. Here, the high-reactivity n-heptane fuel is injected through the CR injector from a start of solenoid energizing (SSE) of 260 crank angle degrees (CAD) to 340 CAD, where 360 CAD is top dead center (TDC) of the compression stroke. The low-reactivity iso-octane fuel is injected using the GDI at 60 CAD for the SNL engine, and is port injected for the ORNL engine. The nominal load is 5.6 bar gross indicated mean-effective pressure (GIMEP). 80% of the fuel energy is delivered by the GDI injection of iso-octane, with the balance delivered by the CR injection of n-heptane, and with a global equivalence ratio of 0.35 for both fuels together.

As the CR SSE timing in Figure 2 is retarded, CA50 begins to advance, yielding a range of “control authority” for which the CR SSE timing can be adjusted to control combustion phasing. In both engines, this range of control authority extends over about 30 degrees crank angle (°CA) of CR SSE timing, yielding a variation of CA50 by 5-7 °CA. At the earliest timings, this control authority is lost near 290 CAD, where further advancement of the CR SSE timing has little effect on CA50. At the very latest CR SSE timings, the effect on CA50 reverses, with CA50 retarding along with the CR SSE. The transition of control authority over CA50 for early injections occurs over a relatively broad range of CR SSE timings, roughly 20 to 30 °CA, as opposed to the late-injection control authority limit that occurs over roughly 5 to 10 °CA. Despite the differences between the two experimental setups (e.g., engine speed, compression ratio, GIMEP), the CA50 data for the two engines are similar. CA50 timings are within 3 °CA or less, and the CR SSE timing of the CA50 minimum is within 5 °CA. This comparison provides some confidence that the in-cylinder imaging observations of combustion behavior in the single-cylinder optical engine are at least generally representative of combustion in the multi-cylinder metal engine.

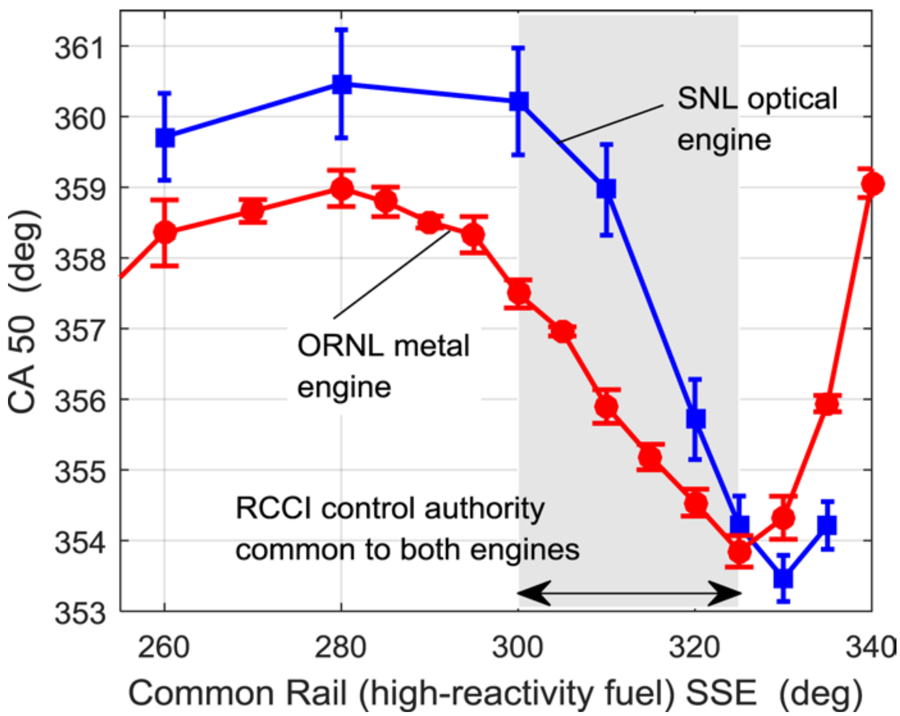

Figure 2. Combustion phasing for both the single-cylinder optical engine (with standard deviation over 36 fired cycles), and the multi-cylinder metal engine (with standard deviation over 4 cylinders during steady-state).

Insight into the in-cylinder mechanisms responsible for the early-injection (near 300 CAD CR SSE) and late-injection (near 325 CAD CR SSE) limits of the range of RCCI control authority may be gained through examination of the optical diagnostic images. Considering first the early-injection control-authority limit, Figures 3 and 4 show series of IR and NL images near the start of the high-temperature heat release at 300 and 310 CAD CR SSE, respectively. The CR injector is in the center of the images, and the piston-bowl wall forms the circular boundary within the image frames. Throughout the series of images in both Figure 3 and Figure 4, IR emission intensity continues to increase throughout the bowl, while the NL intensity first appears where the jets impinge on the bowl wall, and then progresses primarily along the bowl wall. There is also no notable image saturation, indicative of the absence of fuel-rich regions that lead to soot formation. The IR images for 310 CAD CR SSE (Figure 4) show a greater development of HTHR reactions that extend into the interior of the cylinder bowl than for the 300 CAD CR SSE (Figure 3). With less time for premixing, it is expected that locally richer mixtures exist. In comparing the IR image at 350 CAD in Figure 4, for instance, a slightly brighter region exists in the 4 o'clock position near the bowl rim, and this region emits with greater intensity than the corresponding image from SSE = 300 CAD in Figure 3. This slight amount of increased stratification, and subsequent slightly richer local mixtures, is likely an important contributing factor to the change in CA50 control authority.

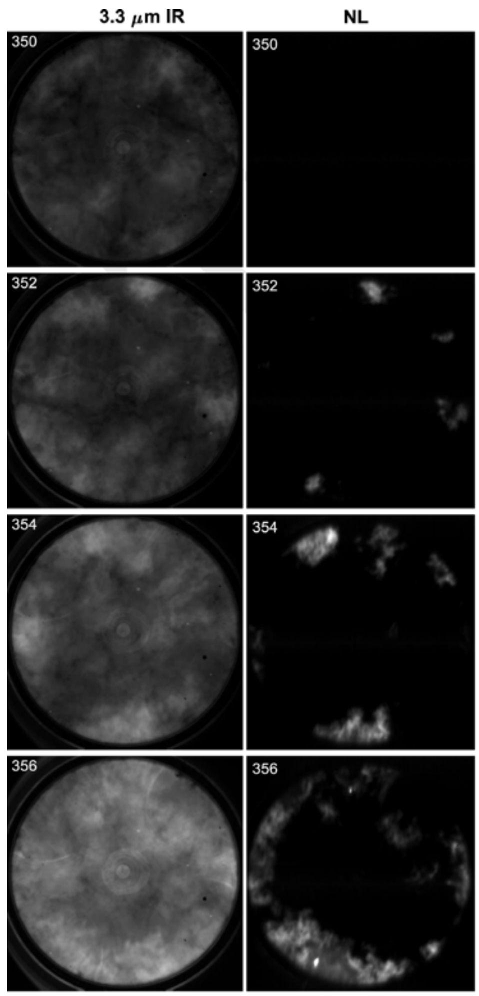

Figure 3. Simultaneous IR and visible NL images, during HTHR period for 300 CAD CR SSE, near the early-injection control-authority limit. Each pair of images corresponds to different combustion cycles, not successive images in time. The imaging crank angle is indicated in the top-left of each image.

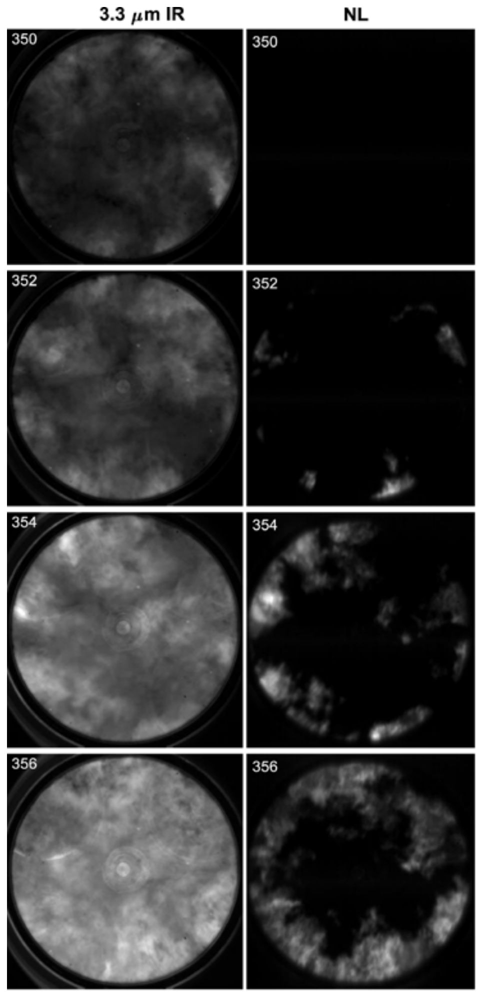

Figure 4. Simultaneous IR and visible NL images, during HTHR period for 310 CAD CR SSE, slightly retarded from the early-injection control-authority limit. Each pair of images corresponds to different combustion cycles, not successive images in time. The imaging crank angle is indicated in the top-left of each image.

For the late-injection control-authority limit, Figure 5 and Figure 6 show series of IR and NL images near the start of the high-temperature heat release at 320 and 330 CAD CR SSE, respectively. The bright-white saturation of the 330 CAD CR SSE NL images in Figure 6 are characteristic of soot incandescence, which indicates mixtures fuel-rich enough that mixing-limited combustion is locally occurring. Increased soot luminosity is also correlated with a change in the apparent heat release rate (AHRR), with the peak AHRR preceding CA50 for 330 CAD CR SSE (not shown). This peak becomes more pronounced and quickly leads to operational limits, specifically as SSE is retarded from 330 to 325 CAD. The turning point in control authority over CA50 (near 330 CAD CR SSE) corresponds to a condition where soot luminosity is both prevalent and persistent (along the entire bowl wall) throughout the entire HTHR period. In the IR images, greater control authority is associated with a higher degree of fuel-vapor dispersion as identified by the loss of clearly defined boundaries between jet structures in Figure 5 compared to Figure 6. Within the range of CA50 control authority, reactivity gradients are apparent in the sequential autoignition that begins along the bowl rim and progresses inward (NL images of chemiluminescence in Figure 4 and Figure 5).

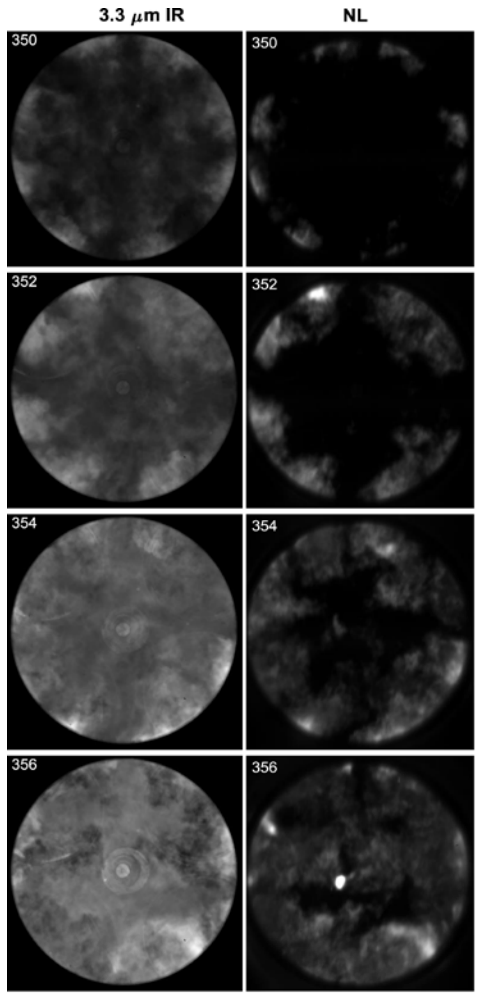

Figure 5. Simultaneous IR and visible NL images, during HTHR period for 320 CAD CR SSE, slightly advanced from the late-injection control-authority limit. Each pair of images corresponds to different combustion cycles, not successive images in time. The imaging crank angle is indicated in the top-left of each image.

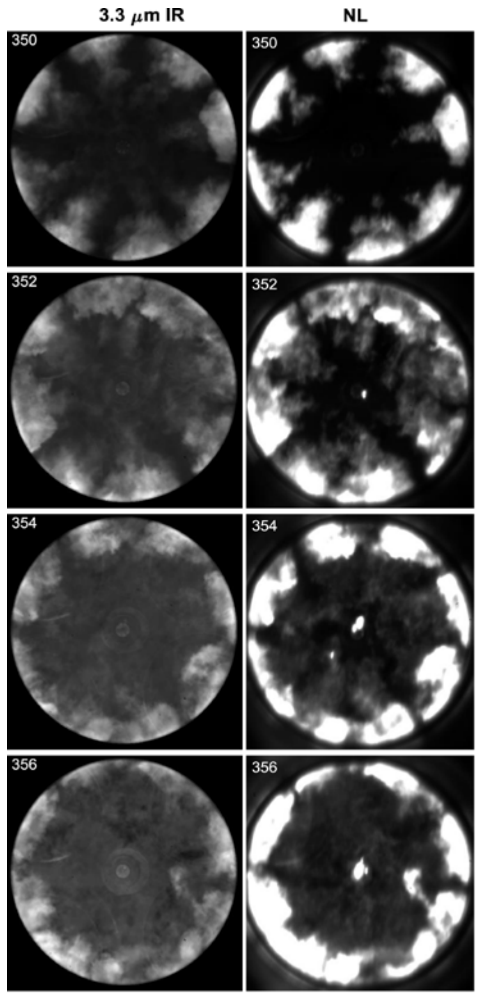

Figure 6. Simultaneous IR and visible NL images, during HTHR period for 330 CAD CR SSE, near the late-injection control-authority limit. Each pair of images corresponds to different combustion cycles, not successive images in time. The imaging crank angle is indicated in the top-left of each image.

Future research will use additional laser/optical diagnostics to measure in-cylinder fuel concentration distributions to help to quantify the effects of those mixture distributions on ignition and combustion. Additionally, fuel properties including volatility and/or reactivity will be varied to better understand the interplay between fuel properties and operating conditions. Together with the all-metal engine experiments at ORNL, these data will help to provide insight into how the load limits of RCCI might be overcome through the Co-Optimization of fuels and engines.

Conclusions

- Developed method to match operating conditions of the SNL heavy-duty single-cylinder optical engine with those of the ORNL light-duty multi-cylinder all-metal engine by using (1) same in-cylinder charge-gas density and temperature at the start of common-rail (CR) injection at the midpoint of the RCCI range of control authority, (2) same premixed iso-octane fraction (80%) with n-heptane CR injection, and (3) same global equivalence ratio (0.35)
- With operating conditions matched, even with different engine displacement (heavy-duty vs light-duty), compression ratios, and piston geometry, the combustion characteristics are similar, with three characteristic regimes of combustion phasing control authority (pre-mixed, RCCI, & mixing-controlled) and similar heat-release shapes

- At the early-injection limit of RCCI combustion phasing control authority, the IR images show low-temperature heat release extending farther into the interior of the cylinder as the CR SSE is retarded. With less time for premixing, stratification increases and subsequent slightly richer local mixtures may well be an important contributing factor to the change in early-injection CA50 control authority limit.
- At the late-injection control-authority limit, loss of control authority is associated with more defined jet structures and less dispersion of the vapor fuel, which also leads to richer mixtures with increase soot formation and subsequent mixing-controlled combustion.

References

RD Reitz, G Duraisamy, “Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines,” Progress in Energy and Combustion Science 46:12-71, 2015.

SJ Curran, Z Gao, VY Prikhodko, AB Dempsey, JM Storey, JE Parks, RM Wagner, “High efficiency clean combustion in light-duty multi-cylinder diesel engines,” Advanced Combustion Engines 2015 Annual Report, DOE Vehicle Technologies Office, 2015

Key Fiscal Year 2017 Publications

1. “Isolating the effects of reactivity stratification in reactivity-controlled compression ignition with iso-octane and n-heptane on a light-duty multi-cylinder engine,” ML Wissink, SJ Curran SJ, G Roberts, MPB Musculus, C Mounaïm-Rousselle C, accepted to Int. J. Engine Research, 2017.
2. “RCCI combustion regime transitions in a single-cylinder optical engine and a multi-cylinder metal engine,” G Roberts, C Mounaïm-Rousselle, MPB Musculus, M Wissink M, S Curran, WE Eagle, SAE Int. J. Engines 10(5), 2017.
3. “Exploratory advanced compression ignition combustion tasks,” S Ciatti, S Curran, J Dec, A Ickes, P Miles, C Mueller, M Musculus, FY17 Vehicle Technologies Office Annual Merit Review Presentation, 2017.

Acronyms, Abbreviations, Symbols, & Units

AHRR	Apparent Heat Release Rate
°CA	Degrees Crank Angle (for duration)
CAD	Crank Angle Degrees (for position, with 360 = TDC compression)
CA50	Crank Angle at 50% mass fraction burned
CMOS	Complementary Metal Oxide Semiconductor (camera)
CR	Common Rail (injector)
FY	Fiscal Year
GDI	Gasoline Direct Injection (injector)
GIMEP	Gross Indicated Mean Effective Pressure
HTHR	High-Temperature Heat Release
IR	InfraRed
NL	Natural Luminosity (soot)
NOx	Nitrogen Oxides
ORNL	Oak Ridge National Laboratory
PM	Particulate Matter
RCCI	Reactivity-Controlled Compression-Ignition
SNL	Sandia National Laboratories
SSE	Start of Solenoid Energizing
TDC	Top-Dead Center