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In-Cylinder Optical Diagnostics of Pre-Chamber Spark Ignition Systems for High-Efficiency Natural Gas Engines

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Pre-chamber spark-ignition (PCSI), either fueled or non-fueled, is a leading concept with the potential to enable diesel-like efficiency in medium-duty (MD) and heavy-duty (HD) natural gas (NG) engines. However, the inadequate science base and simulation tools to describe/predict the fluid-mechanical and chemical-kinetic processes governing PCSI limit the market penetration of PCSI for MD/HD NG engines. Recent efforts outlining phenomenological features of the pre-chamber ignition and subsequent combustion process are presented based on optical diagnostic imaging in a HD optical single-cylinder engine fitted with a PCSI module. Simultaneous infrared (IR) and chemiluminescence (both broadband and OH*) imaging reveal how the pre-chamber ignition-jet emerges from the pre-chamber, mixes with and ignites the premixed main-chamber gases, and subsequently drives the progression of main-chamber combustion, whether by flame propagation or sequential auto-ignition.

Keywords: pre-chamber spark-ignition, lean-premixed natural gas combustion, broadband chemiluminescence, OH* chemiluminescence, infrared imaging

1. Introduction:

Pre-chamber spark-ignition (PCSI), either fueled or non-fueled, is a leading concept with the potential to enable diesel-like efficiency in medium-duty (MD) and heavy-duty (HD) natural gas (NG) engines. By extending the lean-dilution limit and/or the exhaust-gas recirculation (EGR) dilution limit, as well as by shortening the burn duration, PCSI has already demonstrated efficiency improvements of up to 20% in light-duty gasoline engines at low load, achieving diesel-like efficiencies [1]. However, barriers to market penetration of PCSI for MD/HD NG engines, as described in the 2017 DOE NG Vehicle Research Workshop [2] include:

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B1 Inadequate science base and simulation tools to describe/predict the fluid-mechanical and chemical-kinetic processes governing PCSI to enable engineers in industry to optimize designs for efficiency, noise, reliability, pollutant formation, emissions control integration, and drivability [3].

B2 Limited ability to extend EGR and/or lean dilution limits at higher loads [4].

B3 Increased propensity for PCSI hot-spot pre-ignition at high loads relative to conventional spark ignition [4].

B4 Ineffective methane catalysts for the high engine-out unburned fuel concentrations coupled with low exhaust temperatures (<<400 °C) of high-efficiency engines [5].

This work is a portion of an integrated research plan that capitalizes on the existing expertise and core capabilities at four national laboratories (SNL, ANL, ORNL, NREL) in metal- and optical-engine experiments, in-cylinder simulations using computational fluid dynamics (CFD) and chemical kinetics, bench-scale ignition experiments and simulations, and emissions-controls experiments. Here, optical engine experiments are reported that address **B1** by providing phenomenological and quantitative data such as ignition-jet penetration rates, spatial and temporal progression of intermediate combustion species to identify modes of ignition and combustion, and/or sources of combustion inefficiency in the late cycle. Using a PCSI module in a HD optical single-cylinder engine, the ignition-jet is image with multiple optical diagnostics as it emerges from the pre-chamber, mixes with and ignites the premixed main-chamber gases, and subsequently drives the progression of main-chamber combustion, whether by flame propagation or sequential auto-ignition.

2. Experimental Setup:

Figure 1 shows the schematic layout of the optical engine with the imaging setup. The optical-engine is a single-cylinder, Bowditch-piston version of Cummins-N14, heavy-duty diesel with a quiescent (low-swirl) combustion chamber. A flat UV-grade fused-silica piston-crown window provides imaging access from below to the open, right-cylindrical bowl. The engine is fitted with a modular PCSI system consisting of a GM LT4 HDEV5 GDI fuel injector, a miniature Rimfire Z1 sparkplug, and a pressure transducer. The pre-chamber has eight circular, 1.6-mm diameter nozzle orifices with included angle of 130º. A Clean-Air SP010 gas-injector fitted on the intake manifold (0.55m upstream of intake port) fumigates surrogate NG using a perforated annular tube embedded in the intake air-stream. The injector location and long residence-time from injection to induction (4-5 cycles) yields a relatively homogenous premixed NG-air charge. The engine is operated at 1200 rpm in "9:1 skip-fire mode" i.e., pre-chamber spark plug fired in one out of ten cycles. The NG is a surrogate mixture of 95% methane, 4% ethane, and 1% propane by volume.

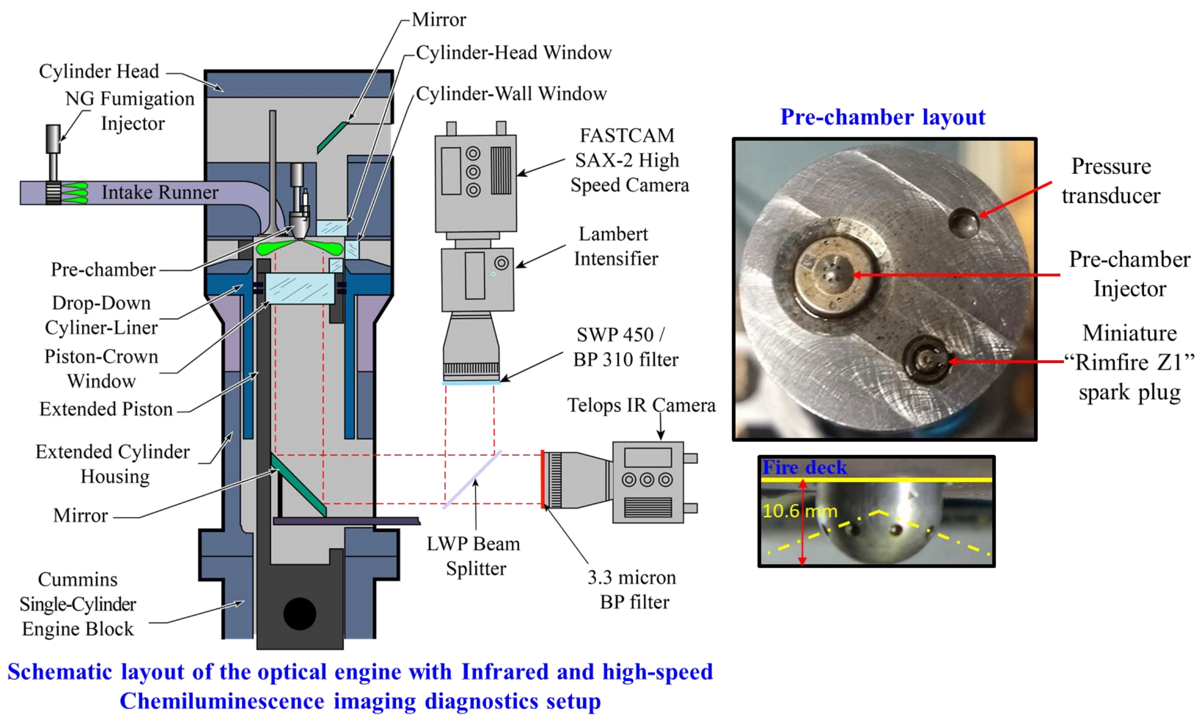

Figure 1. *Schematic layout of the optical engine fitted with pre-chamber spark-ignition system (PCSI) along with the optical diagnostics setup.*

The apparent heat-release rate (AHRR) is calculated from the main cylinder and pre-chamber pressures measured every 0.25-CAD using piezoelectric-pressure-transducers. Pressure data are smoothed using a Fourier-series low-pass-filter with a Gaussian roll-off function (transmission of 100% @ 0-800Hz, 1% at 3360Hz) to remove acoustic ringing while retaining important features of AHRR. Optical diagnostics include crank-angle resolved, broadband-blue chemiluminescence (415-440nm band-pass-filter (BPF), 105-mm glass-lens at f/2.5) and filtered-OH* chemiluminescence (10-nm wide, 310-nm BPF, 105-mm UV-lens at f/8-f/11) captured using a high-speed camera (Photron-FASTCAM-SAX-2) coupled to a high-speed intensifier (Lambert-Hi-CATT-S-20). To quantify the in-cylinder NG concentration and to characterize the pre-chamber jets (tip penetration, spreading angle, etc.), infrared (IR) C-H stretch emission images are captured by a Telops TS-IR MW InSb camera fitted with a Spectrogon 215-nm wide, 3.717-

micron BPF. The IR BPF transmits IR emission from NG arising from C-H vibrational stretching at elevated in-cylinder temperatures achieved during compression prior to combustion, as well as during combustion.

3. Results:

Composite snapshots of IR images (red) overlaid on broadband/OH* chemiluminescence images (green) for pre-chamber only fueling i.e., no NG in the main chamber (λ_{pre} = 1.0), unfueled (passive) pre-chamber ($\lambda_{pre} = \lambda_{main}$ = 1.5) and fueled (active) pre-chamber (λ_{pre} = 0.93, λ_{main} = 2.6) are presented in Figure 2a (broadband chemiluminescence), 2b, and 2c (OH* chemiluminescence), respectively. Overlap of IR and chemiluminescence appears as yellow color. Figure 2a shows weak IR emission at 348 CAD from isolated pockets of fuel, which can only be caused by NG leaking from the pre-chamber into main chamber prior to 348 CAD. At around 350 CAD, weakly emitting IR jets emerge from the pre-chamber as the initial pressure rise in the pre-chamber forces unburned-fuel into the main chamber. The first instance of broadband chemiluminescence appears at 352 CAD, indicating that the propagating flame inside the pre-chamber has reached the pre-chamber nozzles. The observed asymmetry in the emergence of pre-chamber jets is possibly due to charge stratification inside the pre-chamber. This is then followed by increasingly strong IR emission intensity from 351 to 355 CAD that spreads throughout the main chamber, while broadband chemiluminescence is restricted to a small narrow region around the pre-chamber periphery. Reducing IR emission intensity after 358 CAD is likely at least partially due to decreasing temperatures caused by mixing of hot combustion products with cooler surrounding air. In the unfueled pre-chamber (Figure 2b), IR imaging cannot discriminate fuel leakage or emergence of fuel-jets from pre-chamber from the uniform backdrop of NG in the main-chamber. Burning IR jets emerge from pre-chamber by 352 CAD almost simultaneously with OH* chemiluminescence, igniting main-chamber charge by 353 CAD. Most of the progression of OH* chemiluminescence images is consistent with flame propagation, with isolated instances of auto-ignition in the downstream jet after it has emerged from the pre-chamber. For the fueled pre-chamber (Figure 2c), IR imaging again cannot capture fuel-leakage and emergence of fuel-jets from pre-chamber due to the uniform backdrop of NG in the main-chamber. The OH* chemiluminescence intensity is much lower throughout the main-chamber and does not show obvious characteristics of flame-propagation.

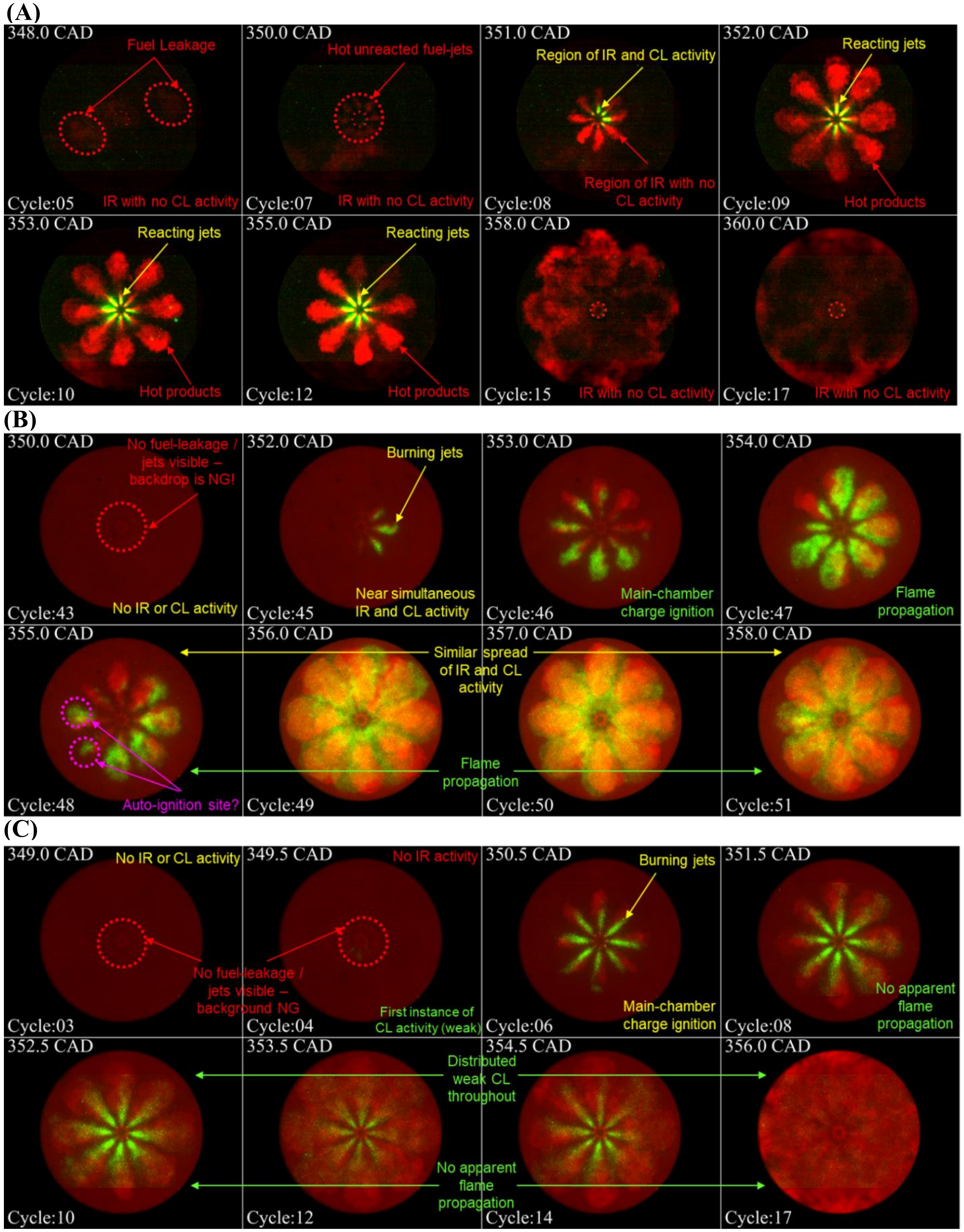

Figure 2. *Composite snapshots consisting of infra-red images (red) overlaid on broadband (a)/OH* (b ,c) chemiluminescence images (green) for (a) pre-chamber only fueling i.e., no NG in the main chamber (λ_{pre} = 1.0) (b) unfueled (passive) pre-chamber ($\lambda_{pre} = \lambda_{main}$ = 1.5) (c) fueled (active) pre-chamber (λ_{pre} = 0.93, λ_{main} = 2.6) .*

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5. References

1. Attard WP, Bassett M, Parsons P, Blaxill H, SAE Technical Paper 2011-01-0664 (2011).
2. Natural Gas Vehicle Research Workshop, https://cleancities.energy.gov/events/13798 (July 2017).
3. Roethlisberger RP, Favrat D, International Journal of Thermal Sciences 42: 239–253 (2003).
4. Shah A, Tunestal P, Johansson B, SAE Technical Paper 2012-01-1980 (2012).
5. Xi Y, Ottinger N, Liu ZG, SAE Technical Paper 2016-01-1005 (2016).