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Towards the Development of a Conceptual Model for Pre-chamber Spark-Ignition High Efficiency Natural Gas Engines

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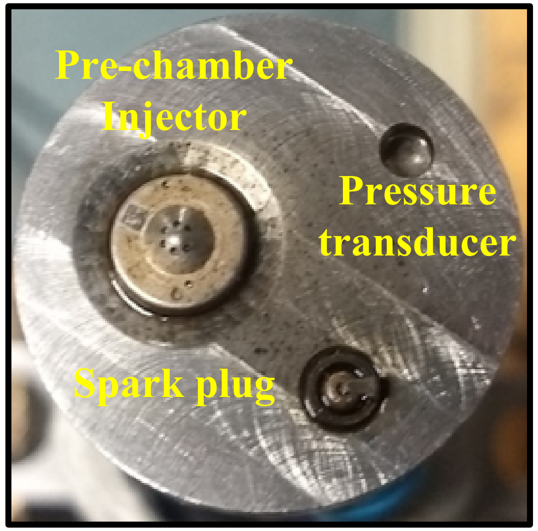
Abstract

The overarching goal of this work is to identify some key elements of a conceptual-model for pre-chamber spark-ignition (PCSI) and to help address the inadequate science base and simulation tools required to describe/predict the fluid-mechanical and chemical-kinetic processes governing PCSI. To this end, experiments performed in a heavy-duty, optical, single-cylinder engine fitted with an active/fueled PCSI module provided fundamental insights on the ignition and subsequent combustion of fuel-lean main-chamber mixtures by a near-stoichiometric pre-chamber. Heat-release analysis coupled with optical diagnostics allowed for tracking spatial and temporal progress of ignition and combustion of lean-burn of NG, while identifying key phenomenological features of PCSI systems.

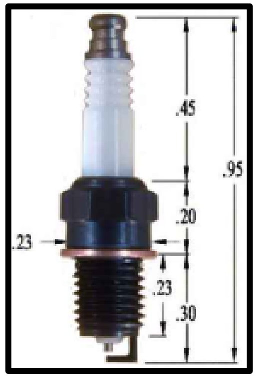
Sandia HD optical engine modified to include fueled natural gas PC. Modular PCSI design with as much commonality as possible are used across all platforms.

Pre-chamber Specifications	
Volume [ml]	4.66
Orifices and diameter [mm]	8 equally-spaced, 1.6
Included angle	130
Modified Compression Ratio	11.03
Spark plug	Miniature rimfire Z1

Pre-chamber layout

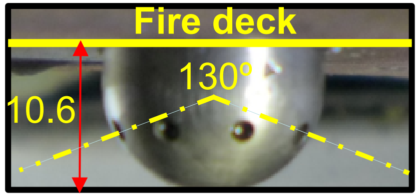


Rimfire Z1 Spark plug



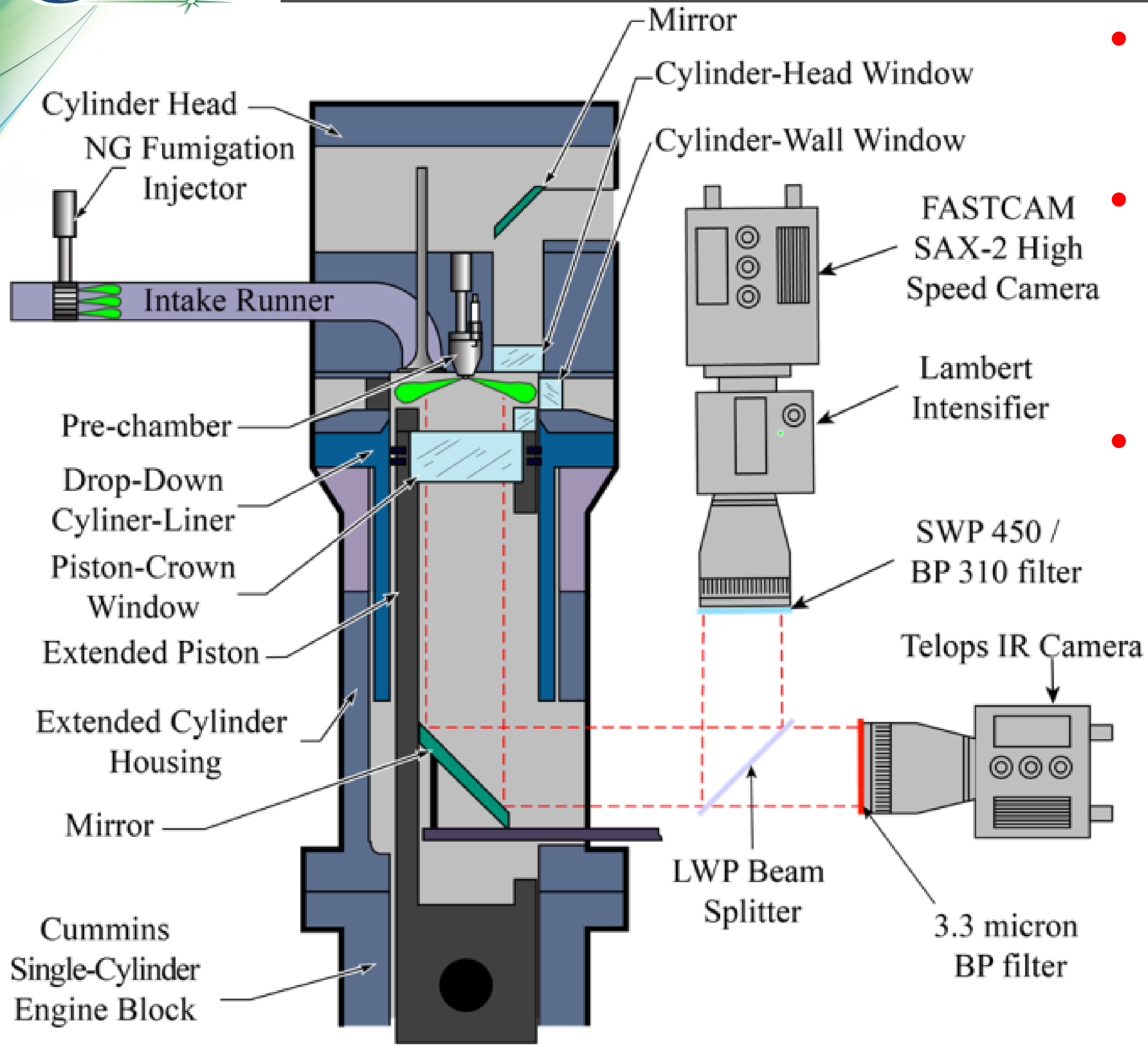
*All dimensions are in inches

NG Pre-chamber Injector Specifications	
Fuel injector type	Solenoid actuated, Bosch HDEV5 GDI
Orifices and diameter [mm]	6 (3 identical pairs) unequally-spaced, 0.17
Fuel	NG (95% CH_4, 4% C_2H_6 1% C_3H_8 by vol.)



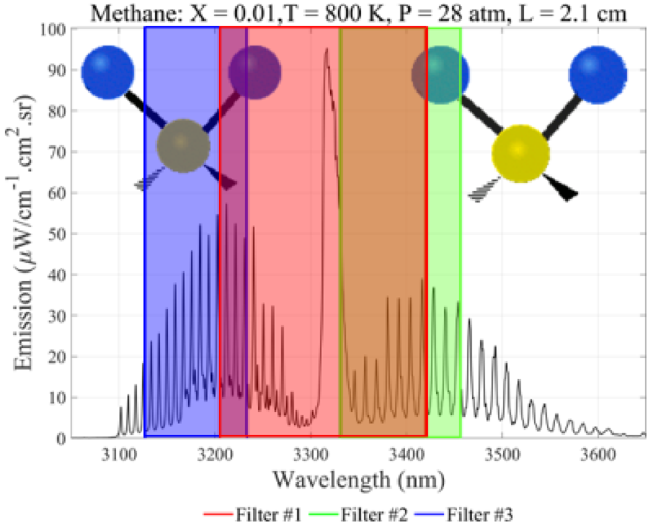
- Number of holes: 8. Hole size: 1.6 mm.
- Included angle: 130.
- 10.6 mm tip protrusion below fire deck.
- Nozzle plane parallel to cylinder head.
- Uncooled piezoelectric pressure transducer.
- GDI fuel injector (SNL / NREL). Check valve (ANL).
- Miniature “Rimfire Z1” spark plug.

IR imaging for characterization of pre-chamber jets.
CL imaging for ignition/combustion location and mode of propagation.



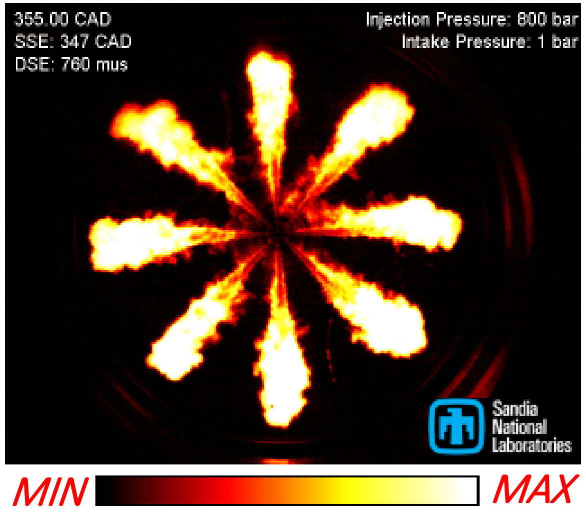
Schematic layout of the optical engine with Infrared and high-speed Chemiluminescence imaging diagnostics setup

- All hydrocarbons emit in the IR near 3.3 µm due to *thermally excited vibration of C-H bonds ("C-H stretch").*
- Filtered IR emission is strong enough for imaging when fuel is heated to above 700 K by compression, providing a means to quickly and easily detect hot in-cylinder fuel.
- *Concentration and Temperature are intertwined.*



Methane Emission Spectrum
(HITRAN Simulation)

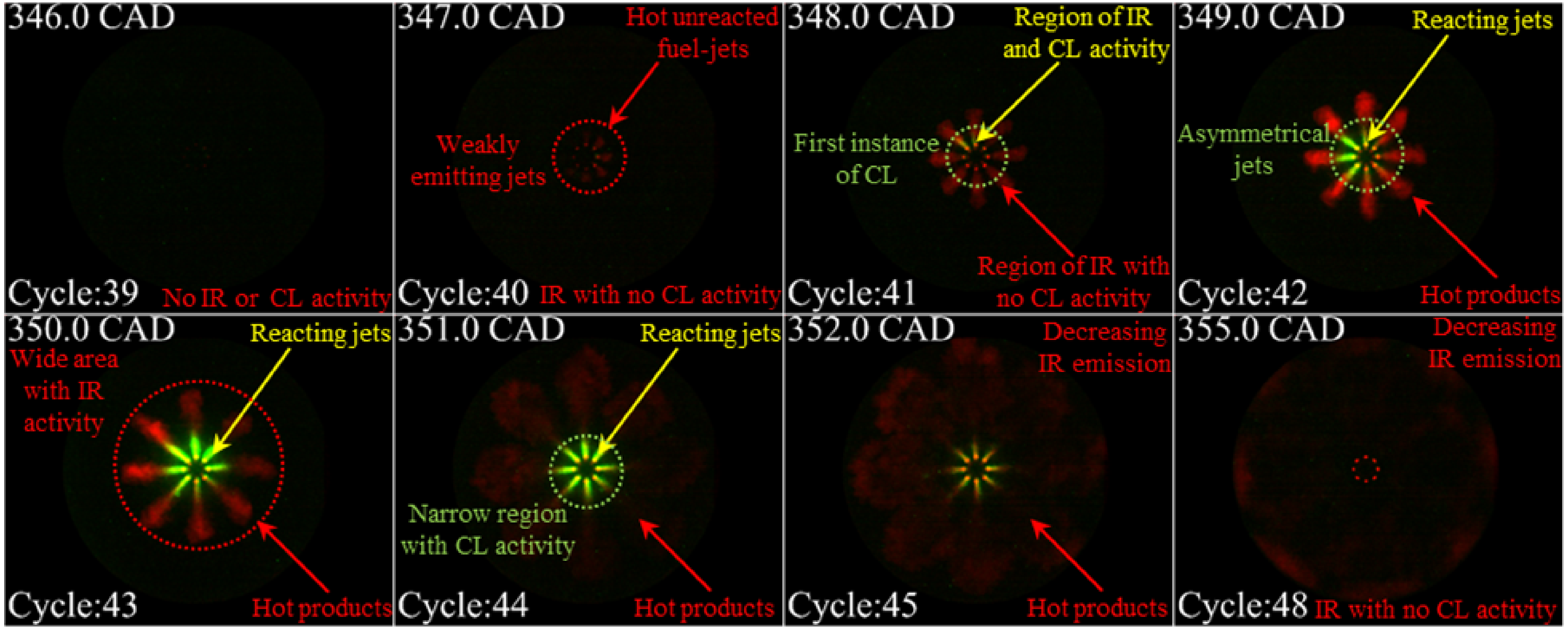
NO COMBUSTION
(Non-reactive inert nitrogen ambient)



FILTERED IR SIGNAL ≡ HOT FUEL

PC only fueling → IR : Unburned fuel-jet precedes burning jet; spreads over wider area;
→ CL : Asymmetry in PC jets; restricted to PC periphery.

Composite snapshots : IR images overlaid on Broadband CL image (simultaneous but non-sequential)

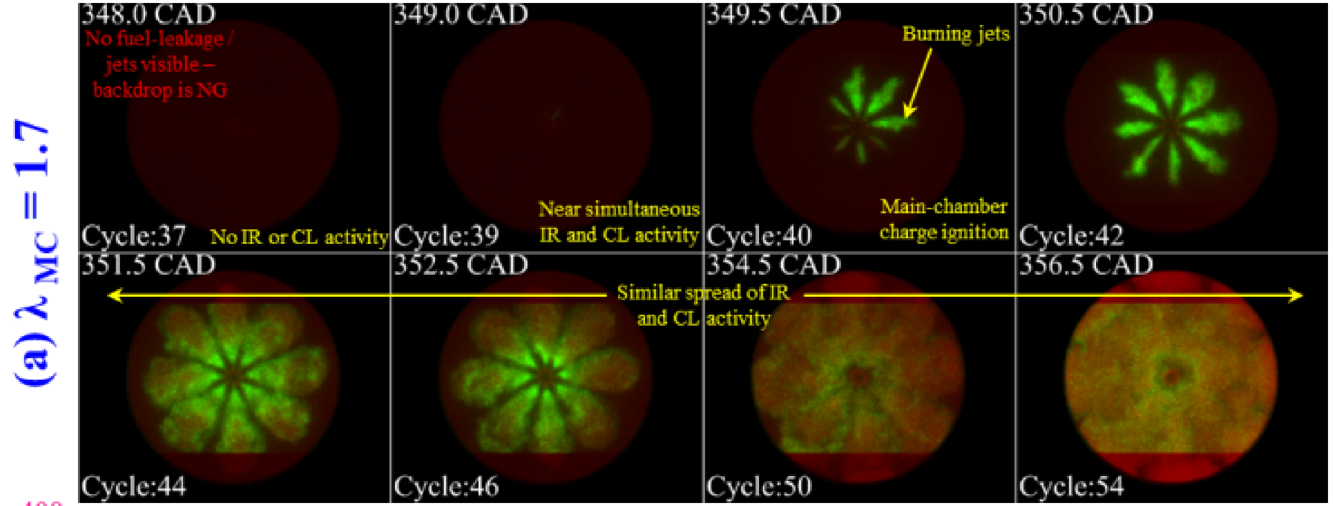


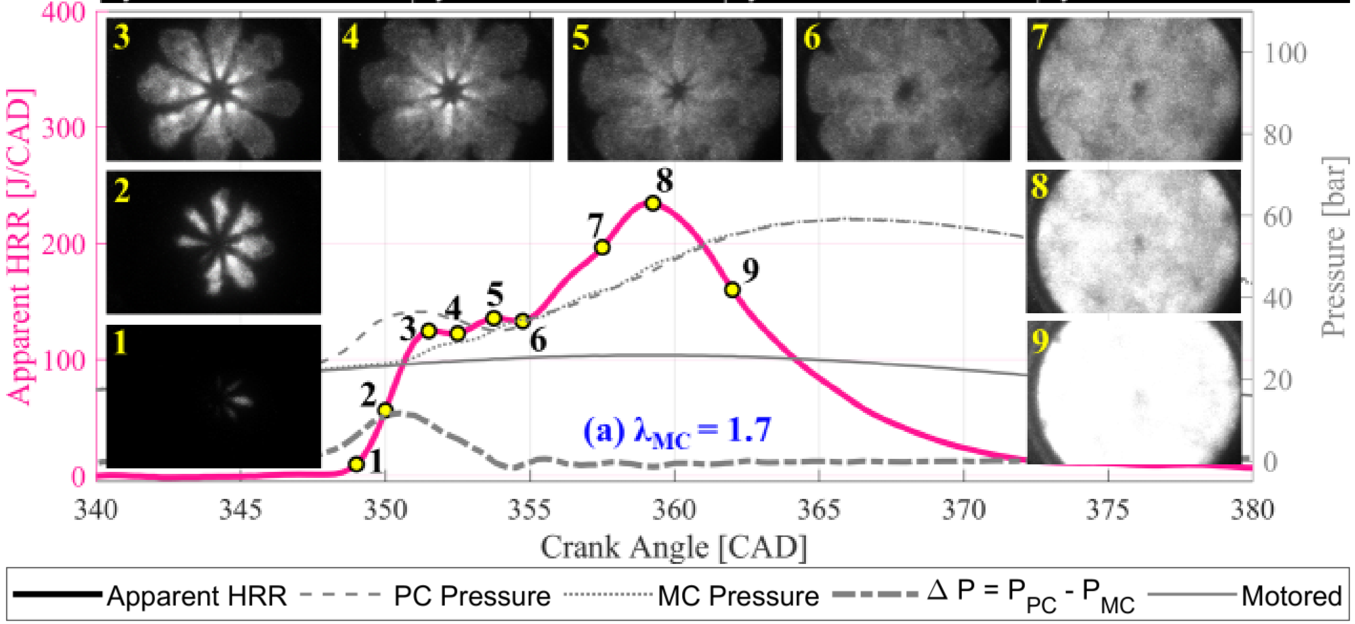
PC only fueling: No NG in MC. λ_{PC} = 0.93*, SSE: 325.75 CAD, DSE: 1517 µs (~ 11º CA), ESE: 336.5 CAD.

- **IR imaging (Red):** Far-field, wider gas jet, high temperature but absence of radical.
- **Broadband CL imaging (Green):** Near-nozzle zone, narrow chemically active jet.
- Asymmetric PC jets : PC charge stratification & stochastic nature of ignition → non-uniformities in shape and direction of initial spark kernel development inside PC → Cycle-to-cycle variations.

λ_{MC} = 1.7: Ejection of unburned fuel-jet is not discernible due to presence of NG in MC. Simultaneous appearance of IR & OH* CL signal at 349.5 CAD (ΔP ~ 3 bar) for all λ_{MC}.

Composite snapshots : IR images overlaid on OH* CL image (simultaneous but non-sequential)

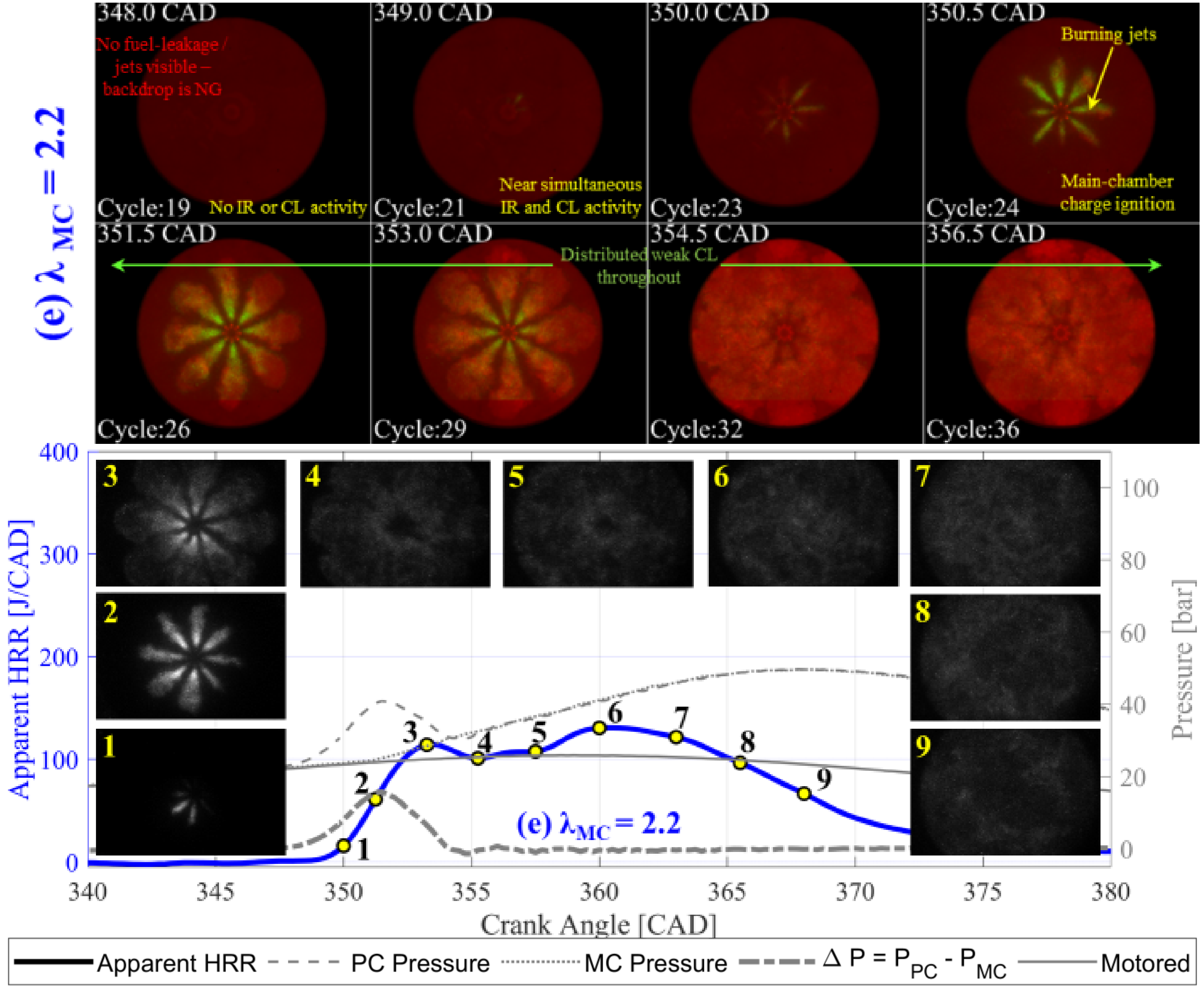




AHRR, ΔP& pressures of PC and MC along with sequential snapshots of OH* CL at key timings. λ_{PC} = 0.93*.

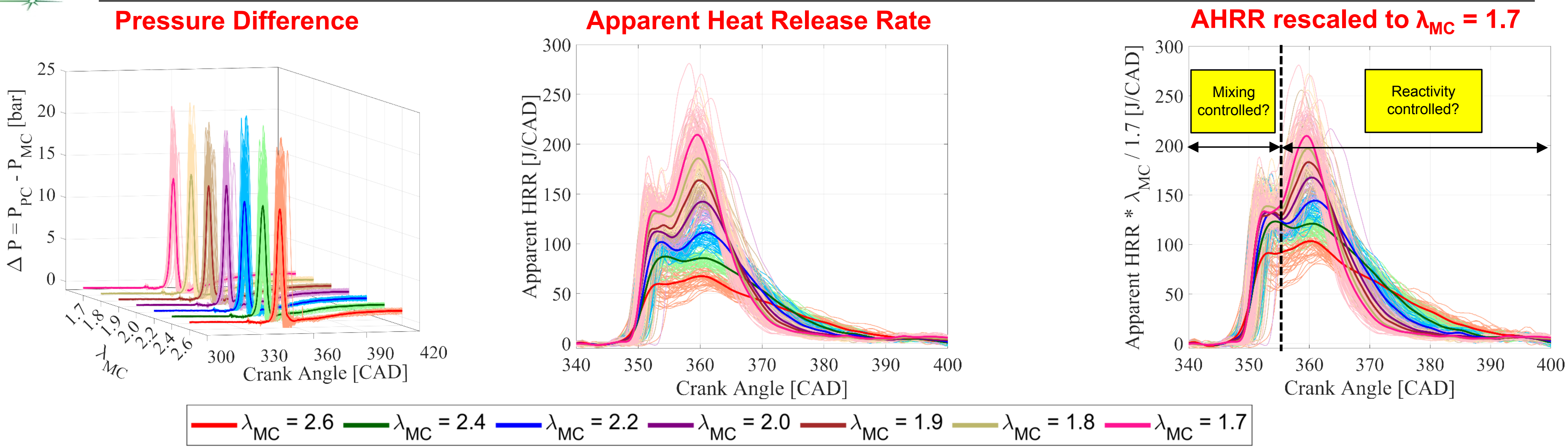
λ_{MC} = 2.2: Near instantaneous ignition of MC charge (within 1ºCA). Bimodal AHRR. PC jets merge → local extinction due to fresh charge unavailability → AHRR local minimum (~355 CAD).

Composite snapshots : IR images overlaid on OH* CL image (simultaneous but non-sequential)



AHRR, ΔP& pressures of PC and MC along with sequential snapshots of OH* CL at key timings. λ_{PC} = 0.93*.

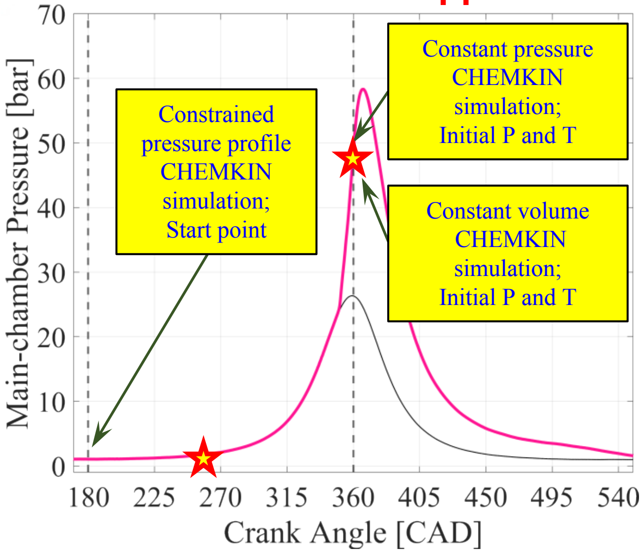
AHRR (until 1st peak) collapses when rescaled to λ_{MC} = 1.7. Identical ΔP. Jet-momentum driven (mixing-assisted/controlled) premixed combustion (controlled by mixing of temperature field).



- PC jets' exit velocity ~ *150 - 200 m/s* independent of λ_{MC} (based on initial OH* images).
- PC jets' tip penetration speed ~ *100 m/s* independent of λ_{MC} (entrainment and viscosity effects).
- *PC jets' speed* is *two orders of magnitude higher* than the maximum achievable *turbulent flame speed* at these conditions → ***Negligible flame propagation***
- *Mixing controlled combustion until 1st peak in AHRR:* MC charge consumed by PC jets penetration (ΔP) and entrainment of surrounding mixture.
- No sequential auto-ignition (Reactivity-controlled combustion).
- Deviations at λ_{MC} > 2.2 → Incomplete combustion or lower temperature slowing the kinetics.

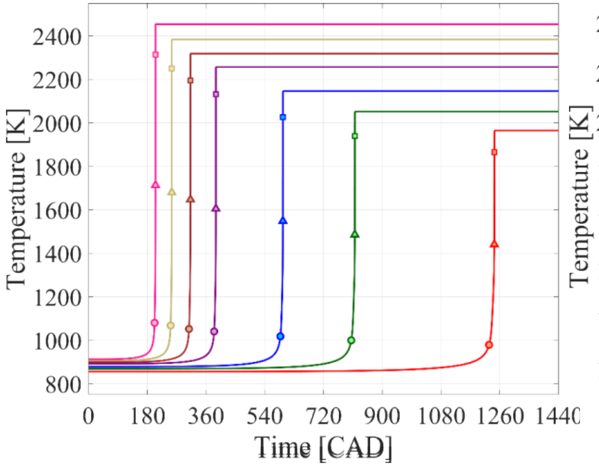
0-D CHEMKIN simulations to assess the extent of reactivity controlled combustion in the later stages of heat release.

CHEMKIN Simulation Approaches

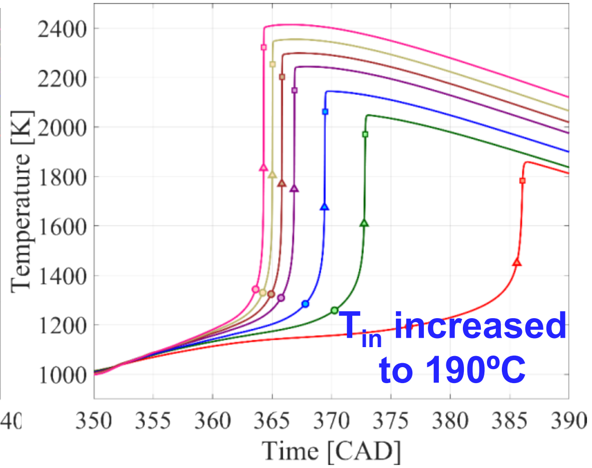


- 3 CHEMKIN simulation approaches using 0-D CHR using AramcoMech version 2.0.
- ***Unrealistically long ID's*** under constant pressure and volume simulations.
- ***Fuel-air mixture does not ignite*** under the imposed pressure profile simulations until *intake T is artificially increased to 190ºC.*
- Despite increased intake T, the trends diverge quickly: Estimated durations increase drastically with λ_{MC}; Experimental values vary by <5 CAD.

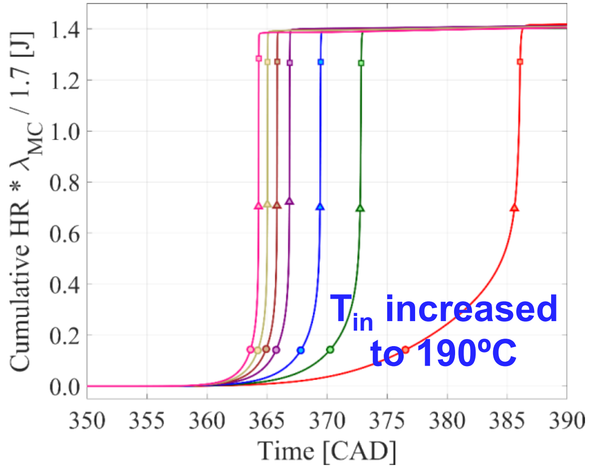
Constant Volume Simulation



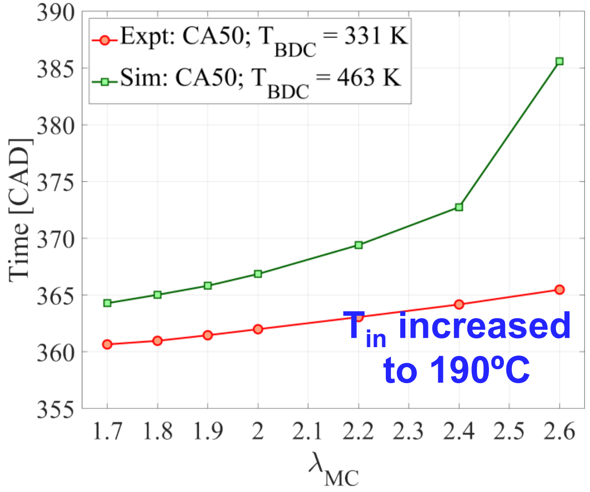
Imposed Pressure Simulation



CHR rescaled to λ_{MC} = 1.7



CA 50 of left over charge

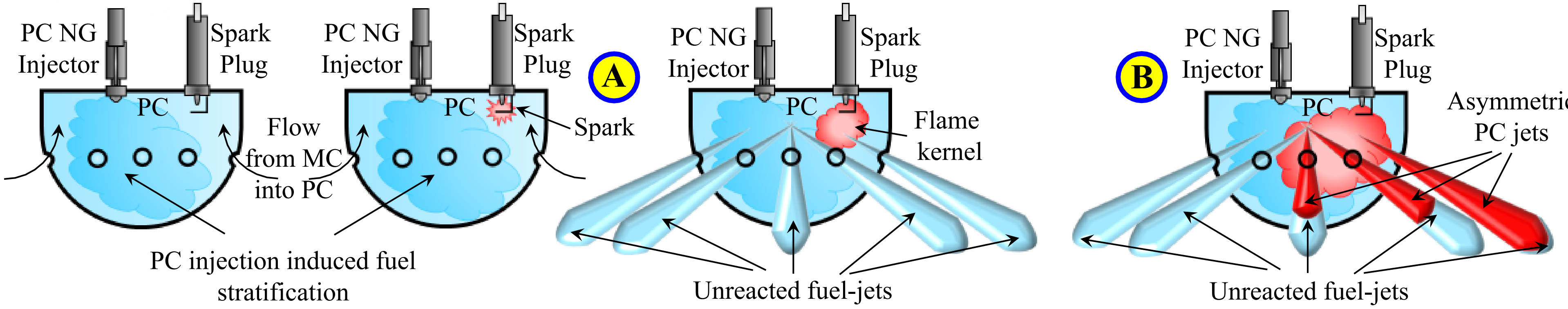


λ_{MC} = 2.6 λ_{MC} = 2.4 λ_{MC} = 2.2 λ_{MC} = 2.0 λ_{MC} = 1.9 λ_{MC} = 1.8 λ_{MC} = 1.7

Conclusions: Elements of initial conceptual model for ignition of fuel-lean MC mixtures by a near-stoichiometric PC

A. ***Unburned fuel mixture is pushed out of the PC before MC ignition, creating a spatially symmetric unburned turbulent fuel-jet pattern in the MC.***

B. ***MC ignition is generally asymmetric as combustion emerges from the PC at different times in different jets.***



C. ***AHRR generally occurs with two stages with a AHRR dip between them.***

i. The *1st AHRR stage is smaller and shorter in duration* and seems to be *mixing controlled,* driven by jet turbulence.

ii. The *2nd AHRR stage is larger and longer in duration* also seems to be *mixing controlled*, potentially driven by in-cylinder bulk flows and associated turbulence and *moderated by chemical kinetics* as MC mixtures become leaner.

D. ***As the MC lean-limit is approached, the general picture of combustion processes seems to remain essentially unchanged, with extended combustion duration.***