Optical-Engine Study of a Low-Temperature Combustion Strategy Employing a Dual-Row, Narrow-Included-Angle Nozzle and Early, Direct Injection of Diesel Fuel

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CATERPILLAR®

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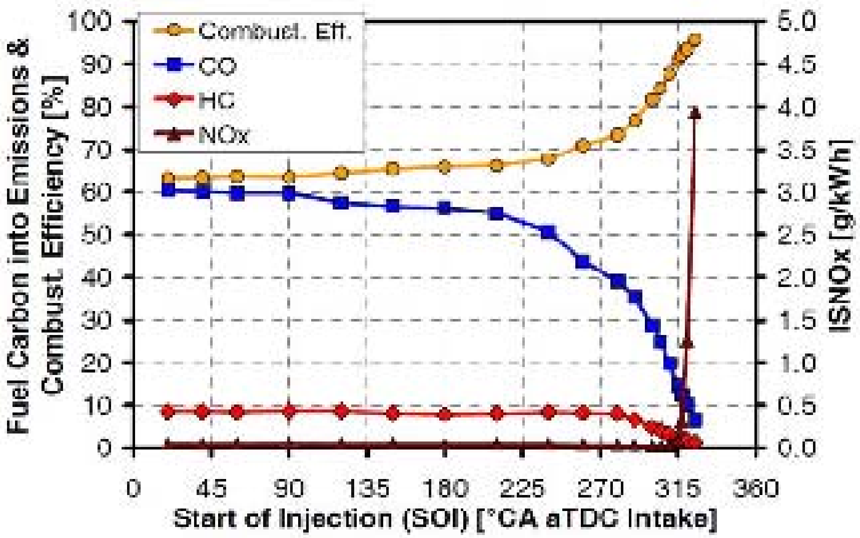
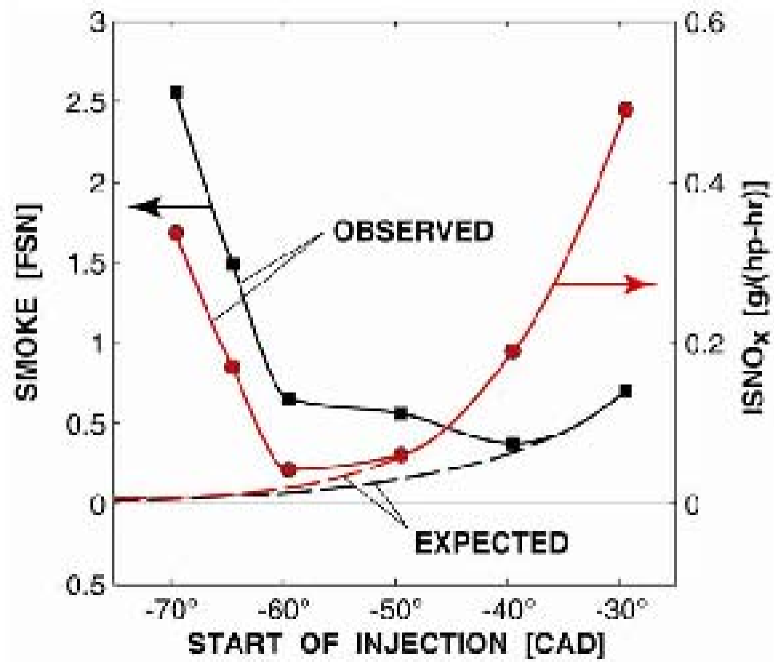
Motivation

- **Early direct-injection (DI), high-efficiency clean-combustion (HECC) strategies are attractive at moderate loads**
- **Why do emissions increase for early-DI strategies that use diesel fuel, when they don't for a gasoline-like fuel (*iso*-octane)?**

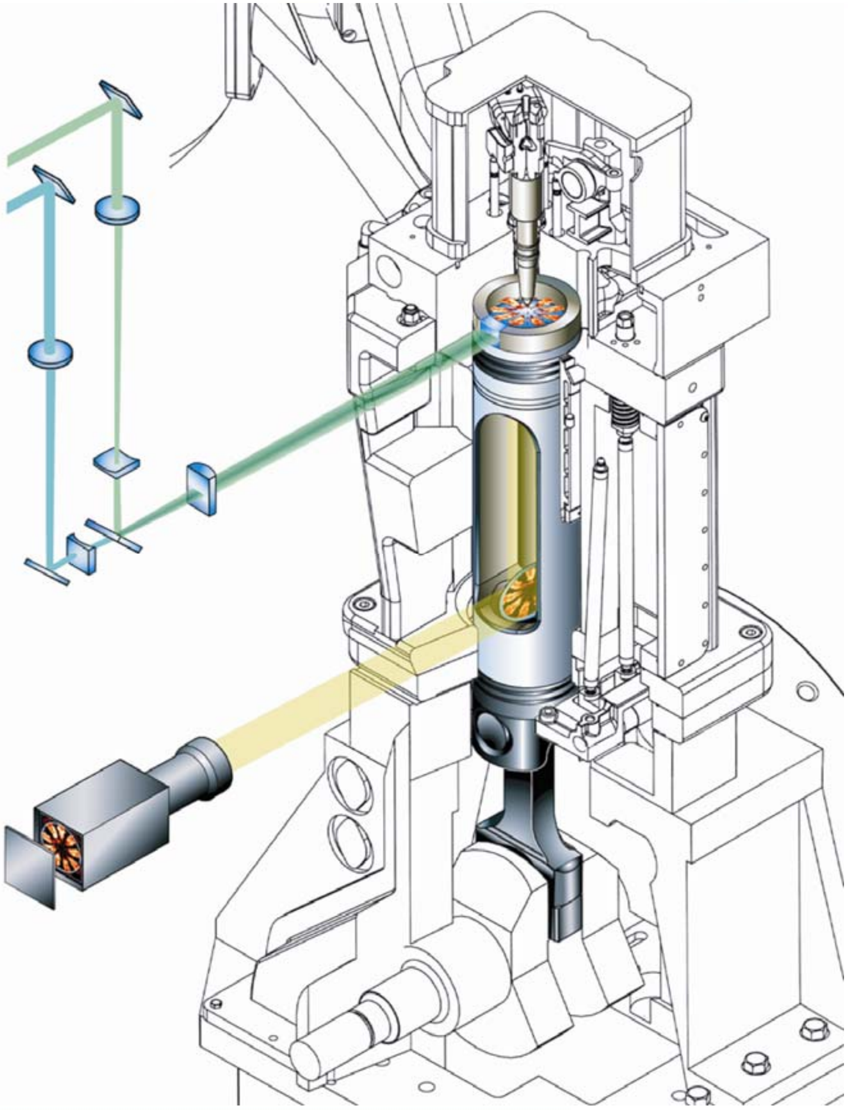


Source: Hwang, Dec, and Sjöberg, SAE 2007-01-4130, Fig. 10



Experimental Approach: Use Sandia Compression-ignition Optical Research Engine (SCORE)

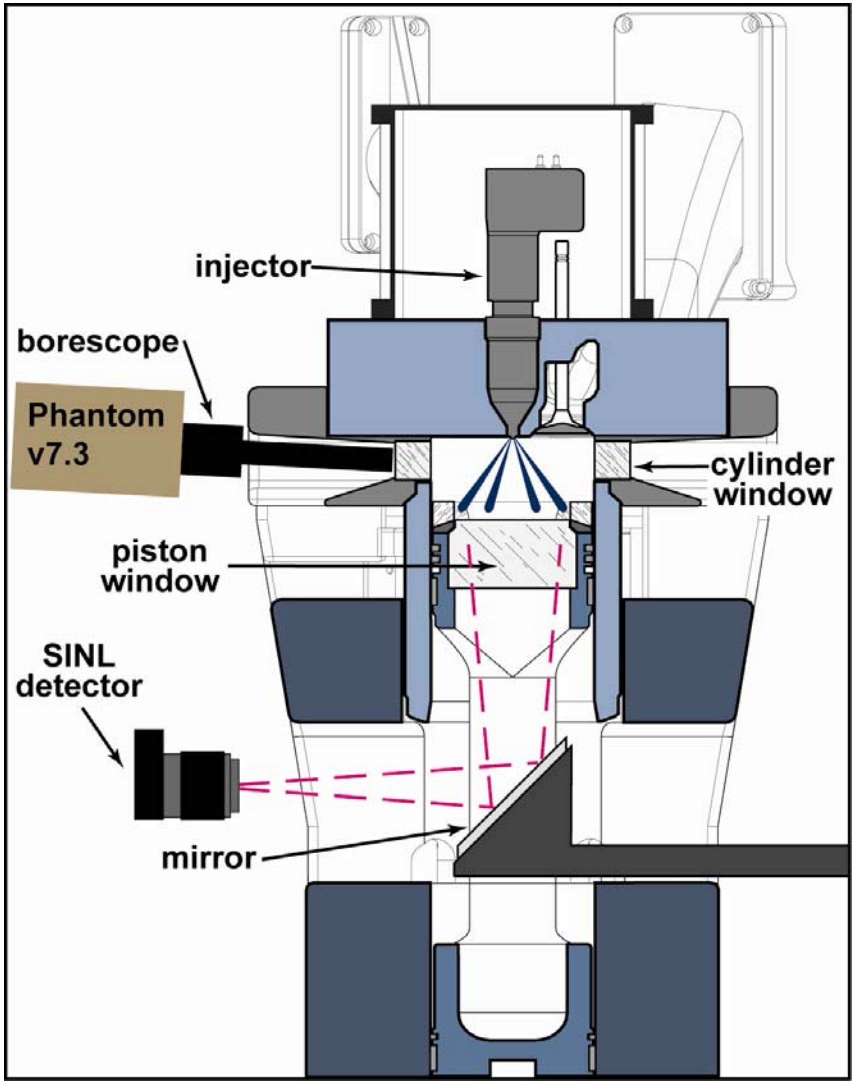
Research engine	1-cyl. Cat 3176
Injector type	Caterpillar HEUI® A
Injector model	HIA-450
Bore	125 mm
Stroke	140 mm
Piston bowl diameter	90 mm
Piston bowl depth	16.4 mm
Squish height	1.5 mm
Swirl ratio	0.59
Displacement per cyl.	1.72 liters
SCORE comp. ratio	11.8:1



- **15-hole, dual-row nozzle**
  - All orifices 103 μm in diameter
  - 10 orifices in outer row
    - 70° included angle
  - 5 orifices in inner row
    - 35° included angle

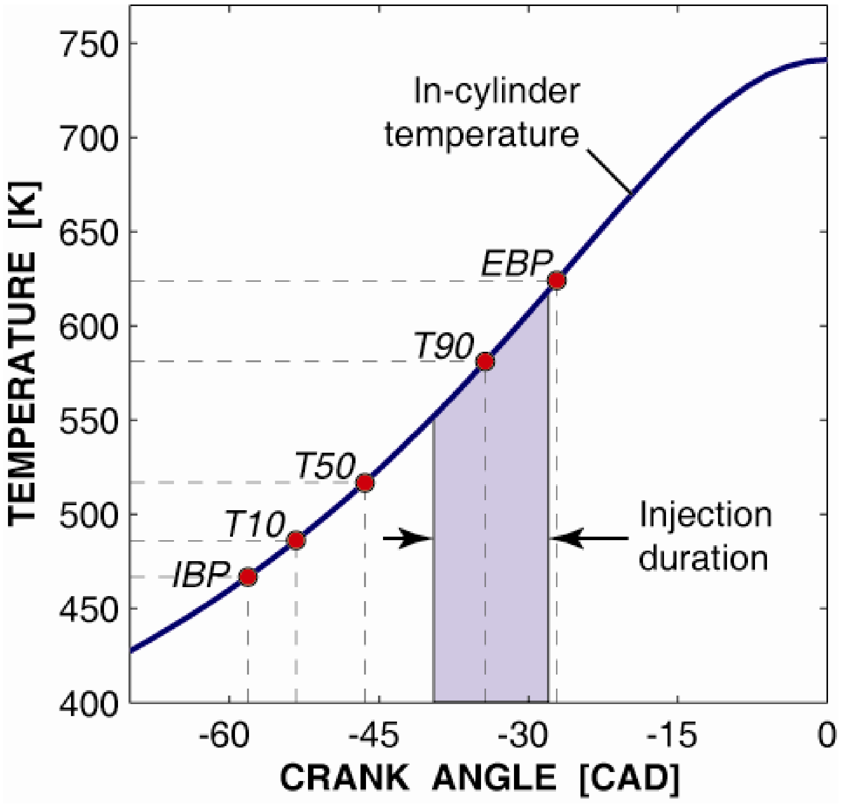
High-Speed Optical Diagnostics

- **Spray visualization**
  - Mie (elastic) scattering from liquid-fuel droplets
  - Illumination from high-intensity discharge lamps
- **Natural luminosity (NL)**
  - Signal dominated by incandescence from hot soot
- **Spatially integrated natural luminosity (SINL)**
  - SINL is time-resolved measure of NL
  - Single-element detector
  - Sensitive from 400 – 1070 nm
- **…plus apparent heat heat-release rate (AHRR) and emissions**



Operating Conditions – Baseline

- **Baseline condition**
  - Constant parameters
    - Speed = 1200 rpm
    - Fuel = #2 ULSD, 45.9 cetane, 34.8 wt% aromatics
  - Swept parameters
    - Start of injection (SOI) = -39.5°
    - Load = 4.82 bar gross IMEP
    - Equivalence ratio = 0.39
    - EGR = 50%
    - Intake temperature = 42 °C
    - Intake pressure = 1.42 bar (abs.)
    - Injection pressure = 142 MPa



- **EGR simulated using N_2 and CO_2 addition to match X_{O2} and c_p of intake mixture with real EGR**

Operating Conditions – Sweep Matrix

	Injection Timing [°ATDC]	Injection Pressure [MPa]	Φ [-]	EGR [%]	Intake Temp. [°C]	Load gIMEP [bar]	Boost [bar]
Baseline Condition	-39.5	142	0.39	50	42	4.82	1.418
Injection Timing Sweep	-69.5 to -29.5	142	0.39	46.6 to 50.2	42	4.82	1.418
Injection Pressure Sweep	-36.3 to -39.5	47, 95, 142	0.39	50	42	4.82	1.418
Equivalence Ratio and Boost Sweep	-39.5	142	0.24 to 0.58	50	42	4.82	2.060 to 1.132
EGR and Boost Sweep	-39.5	142	0.39	30 to 70	42	4.82	1.188 to 1.949
Intake Temperature and Boost Sweep	-39.5	142	0.39	50	32 to 62	4.82	1.373 to 1.508
Intake Temperature and Equivalence Ratio	-39.5	142	0.39 to 0.41	50	32 to 62	4.82	1.418
Load and Boost Sweep	-39.5	142	0.39	50	42	3.82 to 5.83	1.203 to 1.629

Early Injections Lead to Liquid Fuel Impinging on Piston Top

SOI = -69.5° ATDC

SOI = -29.5° ATDC

Absolute gross indicated efficiency is ~3% lower than for conventional operation at a similar load

Sometimes Pool Fires Are Observed in Areas Where Liquid Fuel Impinged…

SOI = -69.5° ATDC

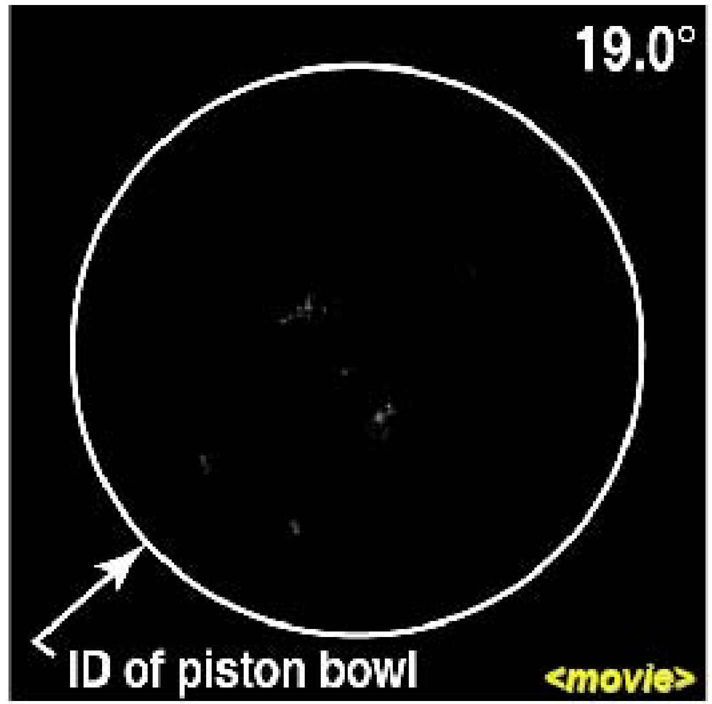
Cylinder-Window View

Piston-Window View

...But Sometimes Little or No Evidence of Pool Fires Is Observed

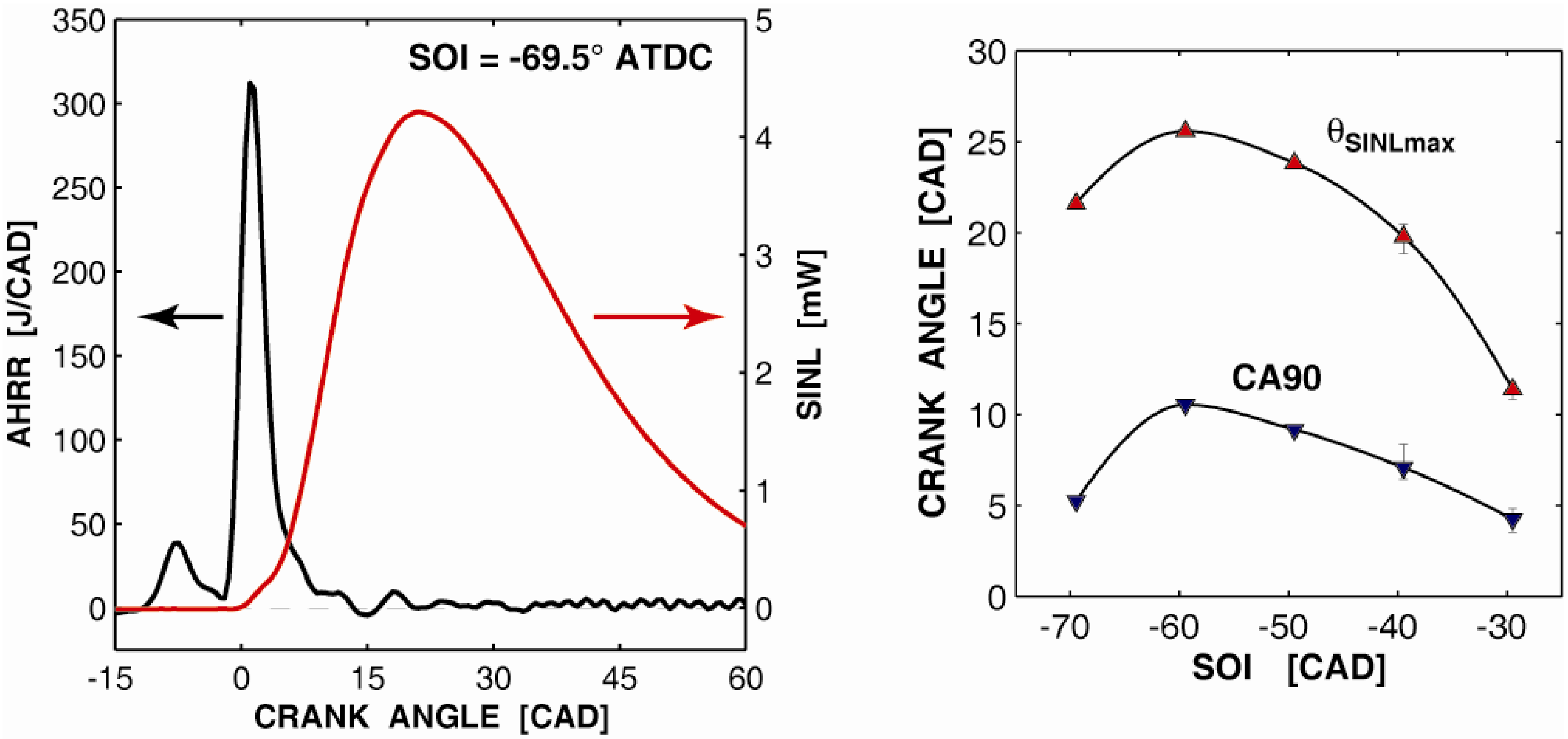
SOI = -39.5° ATDC

Cylinder-Window View



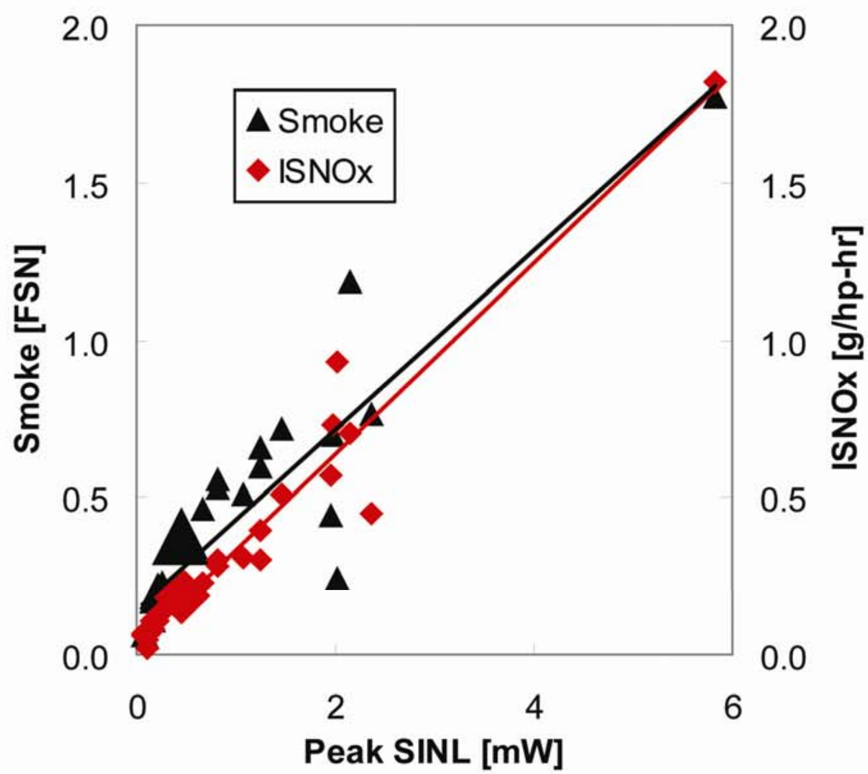
Piston-Window View

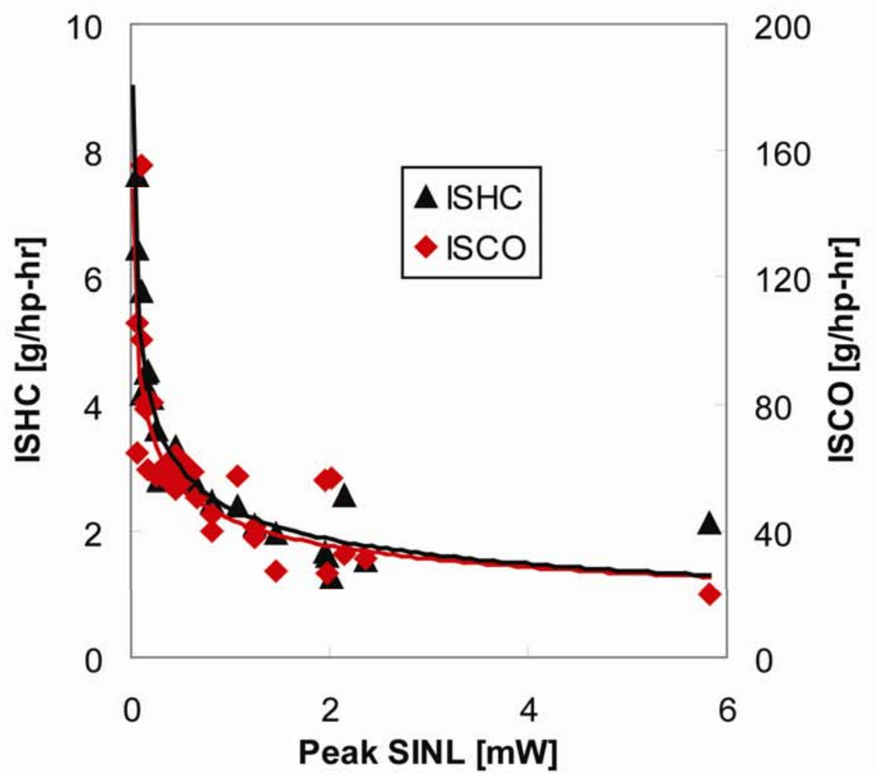
Pool-Fire Activity (i.e., Peak SINL) Is Separate from the Main Heat-Release Event



Main heat-release event produces little SINL, and peak SINL occurs after majority of heat-release has ended

Pool-Fire Activity (i.e., Peak SINL) Is Correlated with Emissions





Data from all two-parameter sweeps

A Hypothesis to Explain How Fuel Films, Emissions, and Efficiency Are Linked

- **If a bright, luminous pool fire is formed:**
  - Fuel-rich regions are producing soot
  - Near-stoichiometric regions around rich regions are producing NO_x
  - Radiative coupling between flame and fuel-film causes film to more-completely vaporize and burn, yielding lower HC and CO emissions
- **If a bright, luminous pool fire is not formed:**
  - Hot soot is not being produced in locally richer regions
  - NO_x may or may not be produced in non-luminous regions, since don't expect to see soot luminosity from regions with $\phi < 2$
  - Lack of radiative heating from flame means incomplete fuel-film vaporization and higher HC and CO emissions
- **Non-optimal phasing, incomplete combustion → lower efficiency**
- **Either way, fuel films lead to problems with emissions and efficiency!**

Summary

- **Liquid-fuel impingement on in-cylinder surfaces can lead to formation of fuel films**
  - Incomplete combustion → lower efficiency
  - Pool fires
- **Fuel films can have a strong effect on emissions**
  - If they ignite, stoichiometric-to-rich combustion can produce excessive soot and NO_x
  - If they don't fully react, can produce elevated HC and CO emissions
- **Looking on the bright side**
  - Since significant emissions and fuel-consumption increases come from fuel films, eliminating them could enable much-improved performance
  - In-cylinder charge motion and/or a higher-volatility fuel could help

For more information, see SAE 2008-01-2400