SAND2015-8990C

Direct-Injection CNG Combustion Research in a Heavy-Duty Optical Engine

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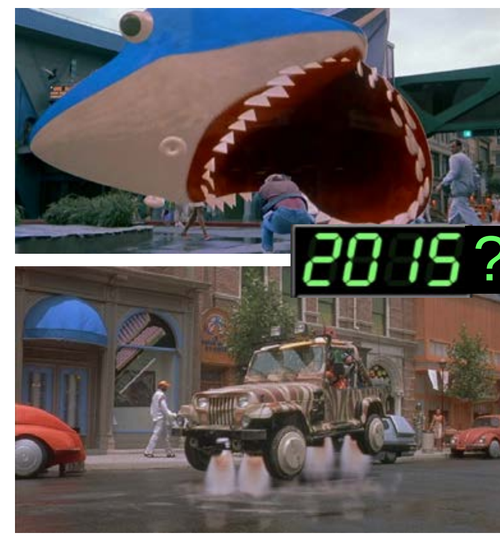
Sandia National Laboratories, USA

Natural Gas Vehicle Technology Forum (NGVTF) 2015 Meeting
Fort Mason Center – San Francisco, CA

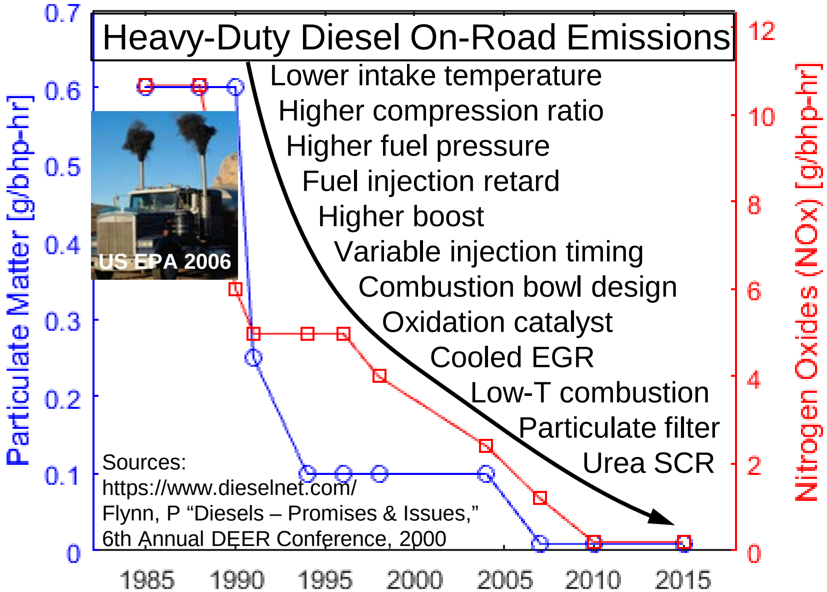
***"Back to the Future Day"* –** October 21, 2015

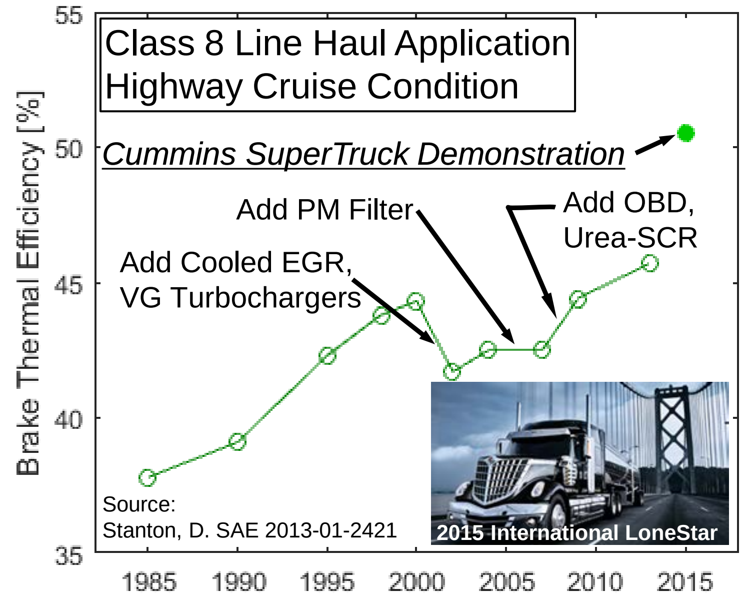


Sponsor: USDOE Office of FreedomCAR and Vehicle Technologies
Program Managers: Gurpreet Singh, Leo Breton, Kevin Stork

1985-2015: Heavy-duty diesel emissions decreased over 50-fold, efficiency up by 8(13) percentage pts.

- Because of its overall fuel-lean charge (λ>1.4 or ϕ<0.7), a conventional diesel engine cannot use the 3-way catalyst for exhaust aftertreatement that has worked well for stoichiometric gasoline (& CNG) engines since 1981
  - Needed to find in-cylinder solutions as emissions targets were tightened through 2004, then add aftertreatment in 2007/2010 (PM filter + Urea SCR)
- Some emissions reduction technologies also brought fuel efficiency improvements
  - DOE SuperTruck 2015 goal/demonstration: 50+% BTE; was <38% in 1985

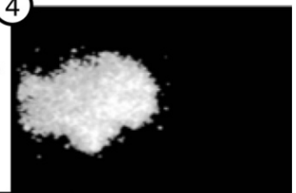


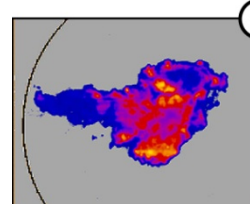


In-cylinder strategies to improve diesel emissions & efficiency were guided by optical diagnostics

O_2 = 21% (no EGR)
SOI = 10 BTDC
P_{inj} = 1000 Bar

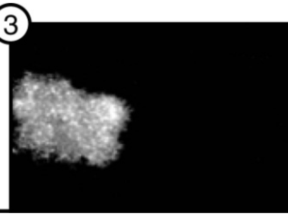
PAH PLIF: Soot Precursors (4)
As hot ignition reactions increase the temperature in the jet, fuel fragments are formed into chemical building blocks for soot.



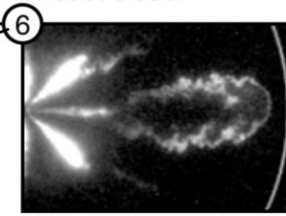


LII: Soot Concentration (5)
Shortly after the premixed fuel burns, soot is formed in the hot, fuel-rich region throughout the jet cross-section.

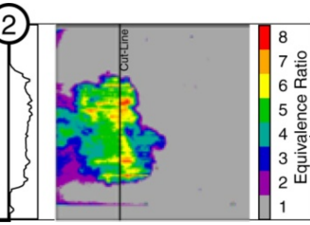
Chemiluminescence: Ignition (3)
Spontaneous ignition reactions occur in the hot mixture of fuel and air throughout the leading portions of the jet.

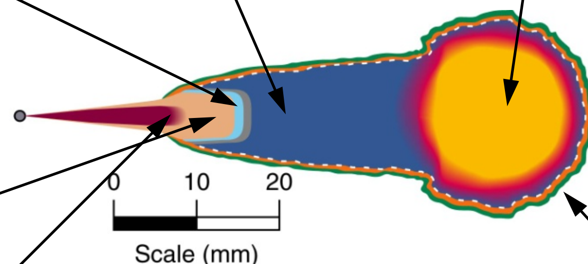


OH PLIF: Diffusion Flame (6)
Shortly after the premixed fuel burns, a thin diffusion flame forms on the jet periphery, surrounding the interior soot cloud.



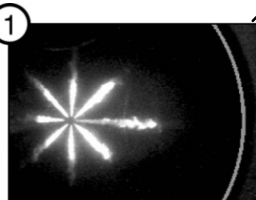
Rayleigh Scatter: Vapor Fuel (2)
The vaporized fuel-air mixture downstream of the liquid is relatively uniform and fuel-rich (Φ = 2-4).





NO PLIF: Thermal NO (7)
NO forms on the periphery of the jet in the hot diffusion-flame products.

Mie Scatter: Liquid Fuel (1)
After penetrating approx. 25 mm, the hot, entrained gases completely vaporize the liquid fuel.



- Liquid Fuel
- Rich Vapor-Fuel/Air Mixture
- Diffusion Flame
- Fuel-Rich Premixed Flame
- Initial Soot Formation
- Thermal NO Production Zone
- Soot Oxidation Zone

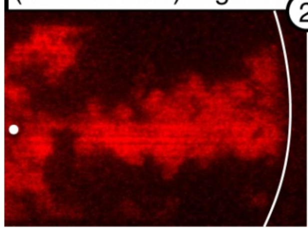
Low — High
Soot Concentration

Source: SAE 970873, Dec (1997)

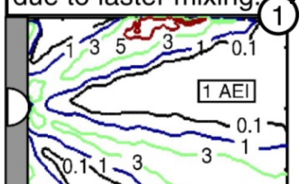
NG studies would need different optical tools. Example: Low-temperature diesel combustion

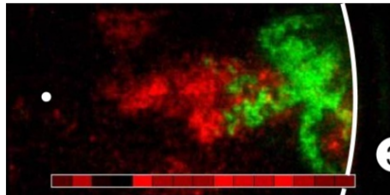
O_2 = 13% (high EGR)
SOI = 22 BTDC
P_{inj} = 1200 Bar

H_2CO PLIF: 1st-Stage Ignition
Formadehyde appears nearly simultaneously in the jet, from fuel-lean (upstream) to fuel-rich (downstream) regions. (2)

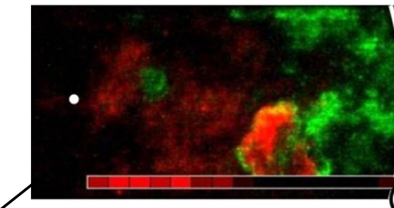


Fuel-Tracer PLIF: Φ
After fuel injection, equivalence ratios decrease and liquid fuel vaporizes rapidly due to faster mixing. (1)

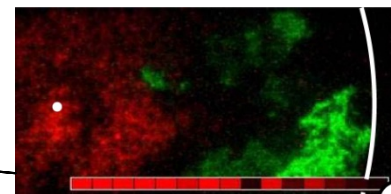




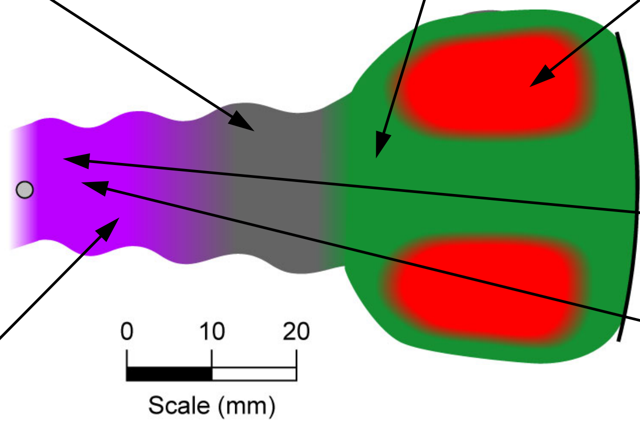
OH PLIF: 2nd-Stage Ignition
OH (green) appears downstream, in wide bands distributed over the width of the jet. Formaldehyde (red) remains upstream. (3)



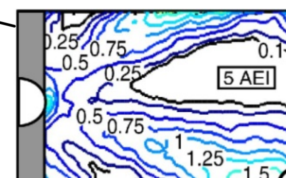
PAH PLIF: Soot Precursors
PAH species (bright red) form near the jet head-vortex, where adjacent jets interact. Formaldehyde (dim red) (4) still remains, upstream.



H_2CO PLIF: Unburned HCs
Late in the cycle, formaldehyde (red) indicates unburned hydrocarbons near the injector. OH (green) indicates combustion (5) is more complete downstream.



First-Stage Ignition | Second-Stage Combustion | Intermediate Ignition | PAH/Soot

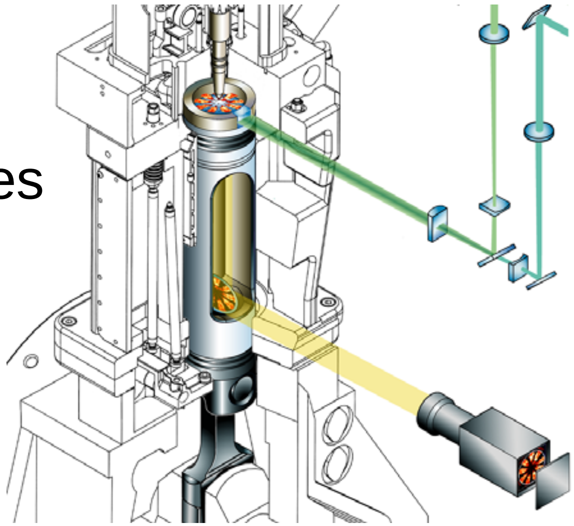


Fuel-Tracer PLIF: Φ
During ignition delay, near-injector mixtures become too fuel-lean to burn completely, (6) leading to unburned HCs.

Source: Prog. Energy Comb. Sci. 39:246-83, Musculus, Pickett, & Miles (2013)

Improvements are needed at many steps in US NG supply/use chain – Sandia/CRF focus is combustion

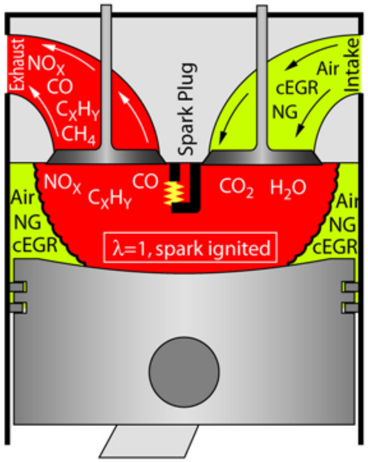
- Key NG R&D areas:
  - Distribution/refueling
  - GTL/LNG production
  - On-board storage
  - **Vehicle end-use: combustion**
- NG optical research is dwarfed by diesel studies:
  - “Optical” + “diesel” SAE papers, 1947-2015: **795**
  - “Optical” + “natural gas” SAE papers, 1992-2015: **45**
- Four NG engine combustion strategies in production:
  - “Best” combustion strategy depends on economics/regulations/performance
  - Each faces unique in-cylinder challenges



Common-platform optical engine capable of 4+ operating strategies to provide missing in-cylinder NG combustion science-base

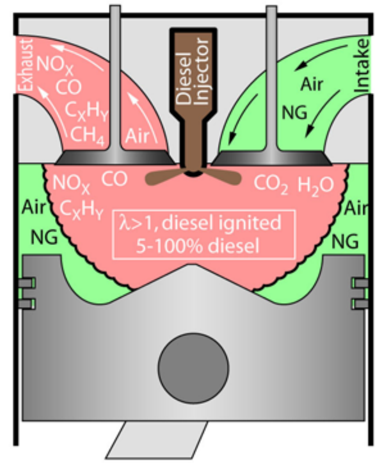
Four production NG combustion strategies today; balance of economics, regulation, & performance

Spark/Prechamber Ignition



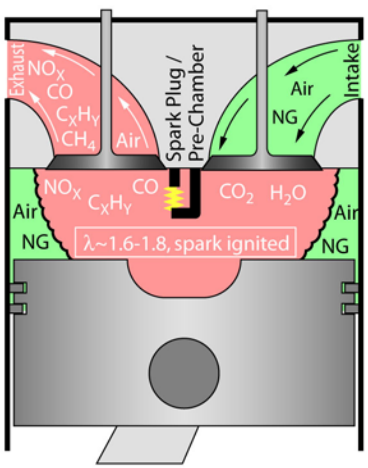
Stoichiometric Spark Ignition

- Port/DI, premixed, cooled EGR
- 3-way catalyst
- ~36% efficiency
- 100% NG
- Cummins, Scania, Waukesha, IVECO



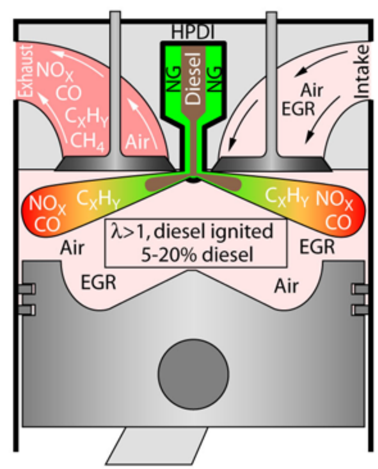
Lean Premixed Diesel Pilot

- Port/DI, premixed or stratified, cEGR
- Oxy-catalyst
- ~45% efficiency
- 0-95% NG
- Volvo (Hardstaff, G-Volution retro.)



Lean Premixed Spark Ignition

- Port/DI, premixed or stratified, EGR
- Oxy-catalyst
- ~44% efficiency
- 100% NG
- Cummins, MAN, Doosan, GE



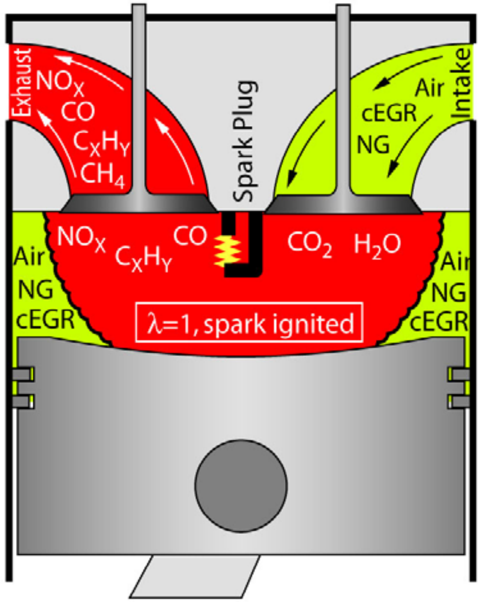
Direct Injection Diesel Pilot

- DI stratified/jets NG+diesel, EGR
- Catalyzed DPF, Urea SCR
- ~46% efficiency
- ~90% NG
- Westport, Volvo

Diesel-Pilot Ignition

Each NG strategies faces unique combustion challenges

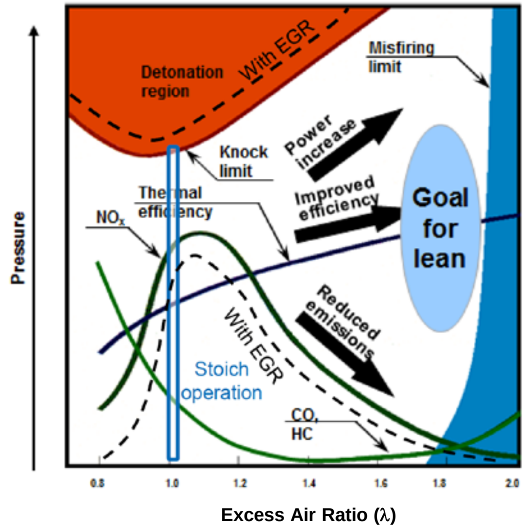
Stoichiometric spark-ignition challenges include efficiency, fuel variability, and knock/load limits



Intake	Premixed NG, Stoichiometric	Methane-specific 3-way catalyst for CO, HC, NOx
	Cooled EGR	Reduces NOx & heat load, raises knock limit
Fuel Efficiency	Low (~36%)	Throttle, Timing Retard, EGR + low compression ratio to avoid knock
NG Fraction	100%	No diesel fall-back
Key HD Dev.	Cummins, Scania, Waukesha, IVECO	

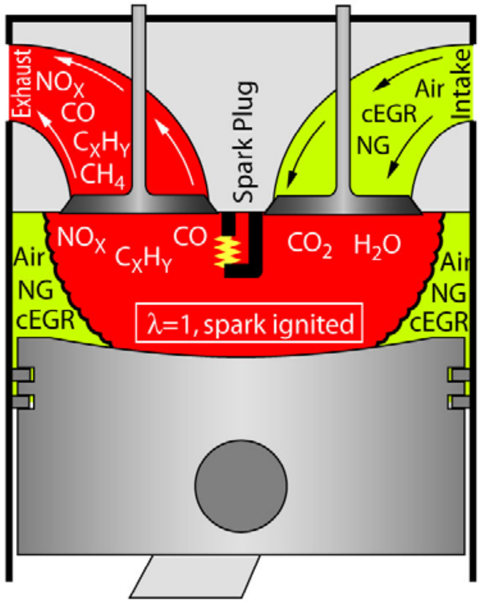
In-cylinder gaps for NG stoichiometric/EGR spark ignition

- Controlling flame kernel/growth/knock transition
  - Surface/geometry effects
  - Fuel composition effects
  - EGR/fuel mixing/distribution effects
- Using turbulence to increase flame speed with EGR
  - Effects on ignition, misfiring issues



* IMechE S1807, Cornwall, Foster, Noble (Ricardo)

Stoichiometric spark-ignition challenges include efficiency, fuel variability, and knock/load limits



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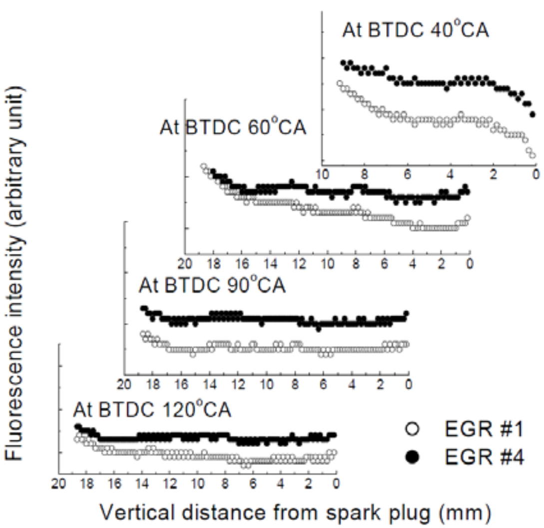
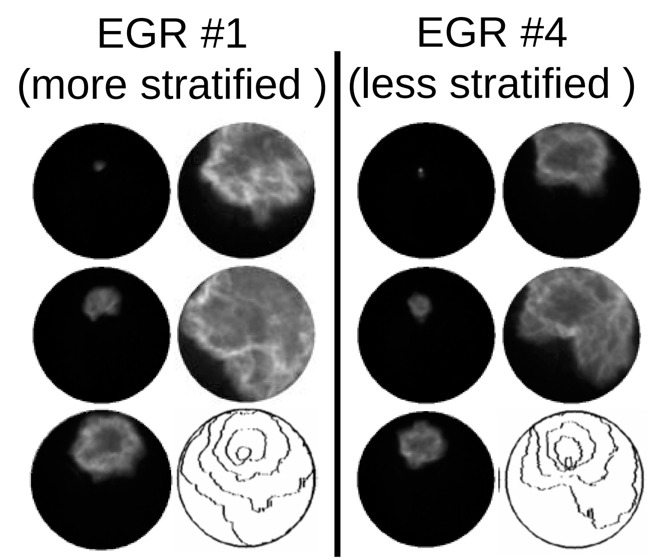
	Cooled EGR	Reduces NOx & heat load, raises knock limit
Fuel Efficiency	Low (~36%)	Throttle, timing retard, slow flame speed, EGR + knock-limited comp. ratio
NG Fraction	100%	No diesel fall-back
Key HD Dev.	Cummins, Scania, Waukesha, IVECO	

<u>Previous optical work:</u>

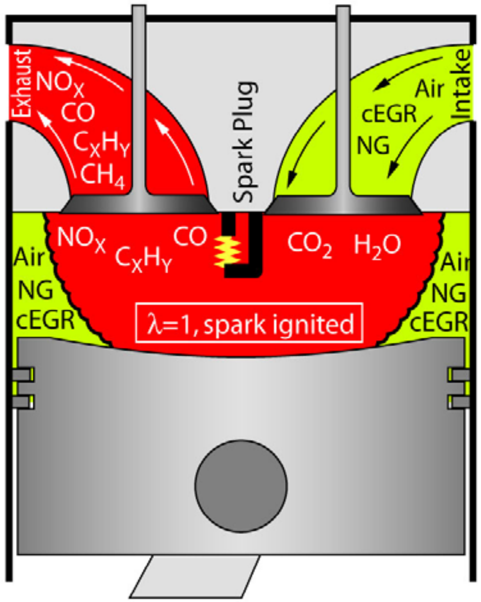
- With LPG, intake port valve can place EGR in bottom of cylinder
- More stratified EGR burns faster and with higher efficiency

* SAE 2004-01-0928, Woo, Yeom, Bae (KAIST); Oh, Kang (KIMM)





Stoichiometric spark-ignition challenges include efficiency, fuel variability, and knock/load limits



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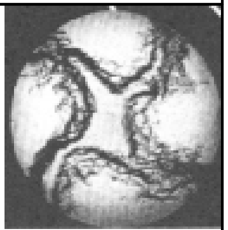
Understand factors that control NG knock with EGR

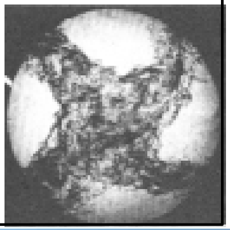
- Kernel/flame growth
- Surfaces/geometry
- Fuel composition (inc. H_2)
- EGR distribution
  - Mixing diagnostics

Schlieren images of knocking combustion

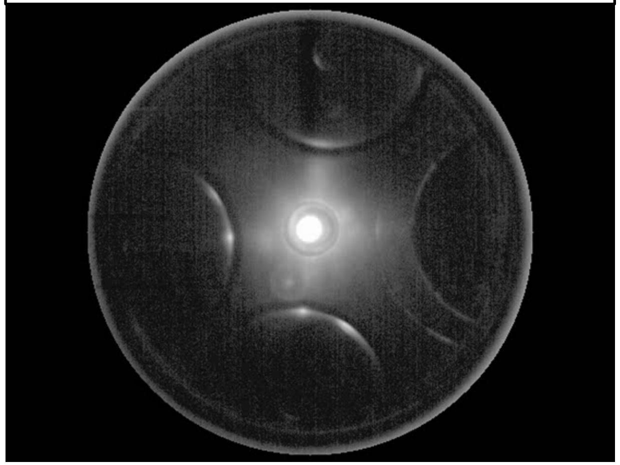
Prior to autoignition of end-gas



Onset of knocking

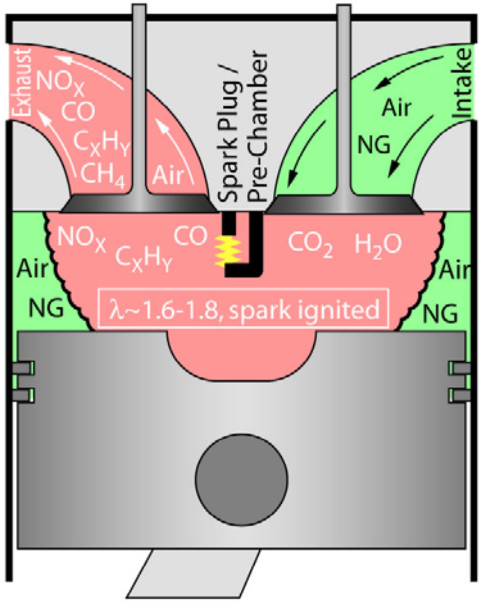


High-speed chemiluminescence imaging of knock-free combustion



* Proc. Comb. Inst. 20, Smith, Green, Westbrook, Pitz (1984)
** www.sandia.gov/ecn/tutorials/visualization.php

Lean premixed spark-ignition challenges include ignition stability, transients, and CH_4 slip



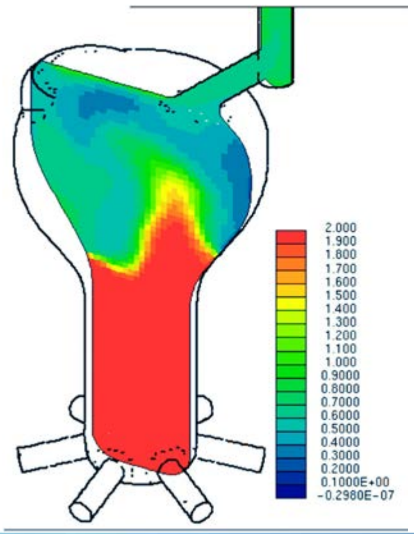
Intake	Lean-premixed NG (λ~1.6-1.8)	Aftertreatment for HC and CO only
Efficiency	~44%	high specific heat ratio, high compression ratio
Heavy-Duty	Cummins, Scania, MAN, GE (Jenbacher)	
Challenges	Ignition stability (pre-chamber), transients, SCR for US2010/Euro VI NOx, CH_4 slip (low exhaust T / catalyst-efficiency)	

Previous optical work:

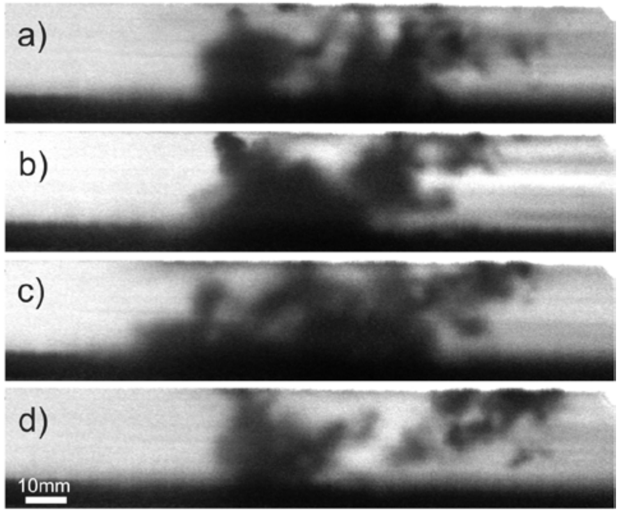
- PLIF shows pre-chamber stratification, comp. inflow
  - Variability lowers knock limit
- Pre-chamber-jet mixing increases flame speed

* SAE 2014-01-1330 Wellander, Rosell, Richter, Alden, Andersson, Johansson (Lund); Duong, Hyvonen (Wartsila)

Pre-chamber simulation



Acetone PLIF: fuel consumption



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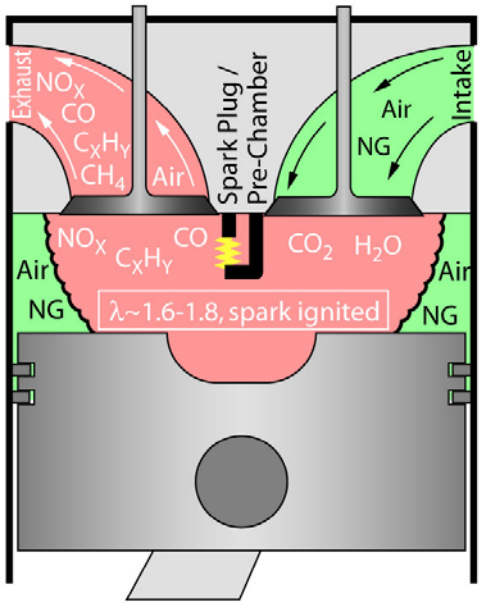

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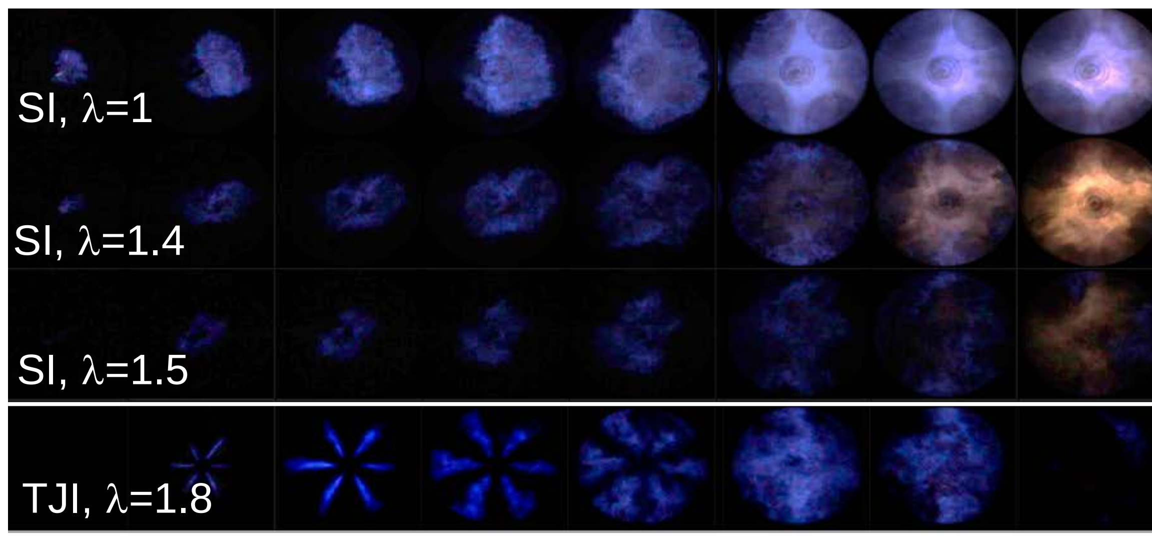
Natural Luminosity imaging

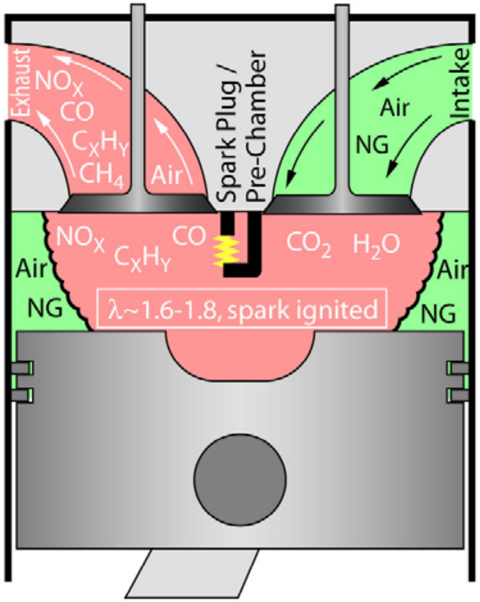


Previous optical work:

- Turbulent jet ignition pre-chamber allows leaner operation with higher stability & combustion efficiency

*SAE 2012-01-0823, Attard (MAHLE); Toulson, Huisjen, Chen, Zhu, Schock (Michigan State U)

Lean premixed spark-ignition challenges include ignition stability, transients, and CH_4 slip



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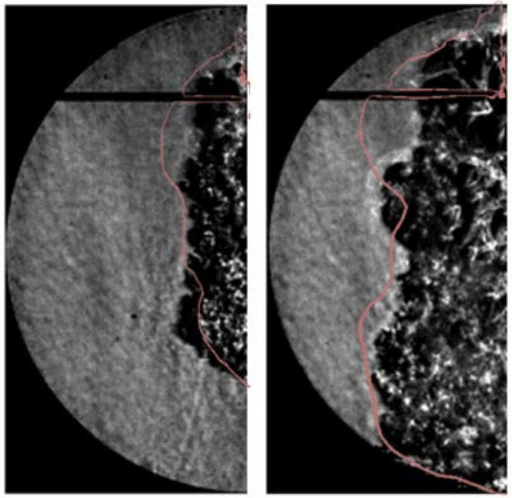
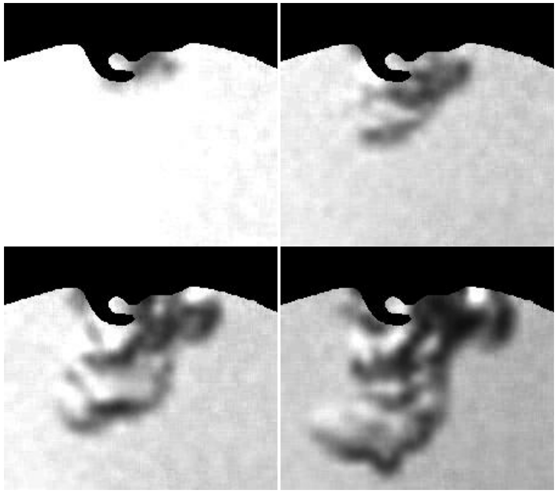
Schlieren spark-ignited jet*



Schlieren jet-capillary spark plug**

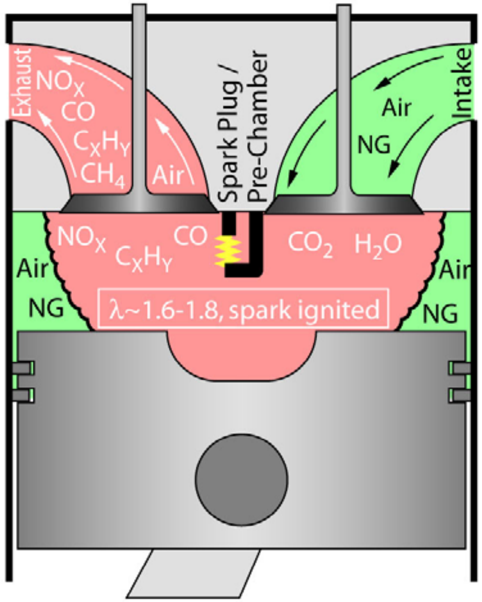


Previous optical work:

- Spark-ignited jets improve combustion speed/stability at overall lean conditions

* SAE 2015-01-0398, Bartolucci, Cordiner, Mulone, Rocco (Rome Tor Vergata); Chan (U British Columbia)
** SAE 2007-01-1913, Chan, Evans, Davy (U British Columbia); Cordiner (Rome Tor Vergata)

Lean premixed spark-ignition challenges include ignition stability, transients, and CH_4 slip



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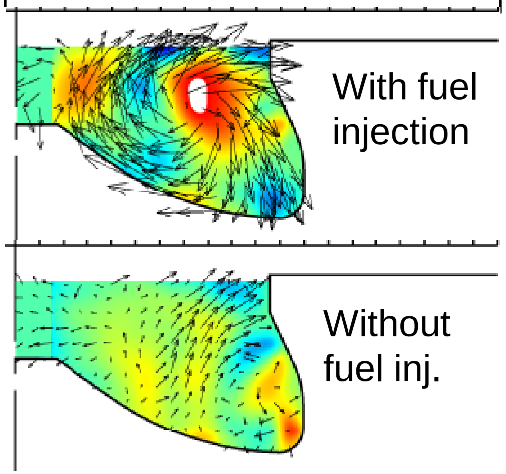
Challenges	Ignition stability (pre-chamber), transients, SCR for US2010/Euro VI NOx, CH_4 slip (low exhaust T / catalyst-efficiency)	

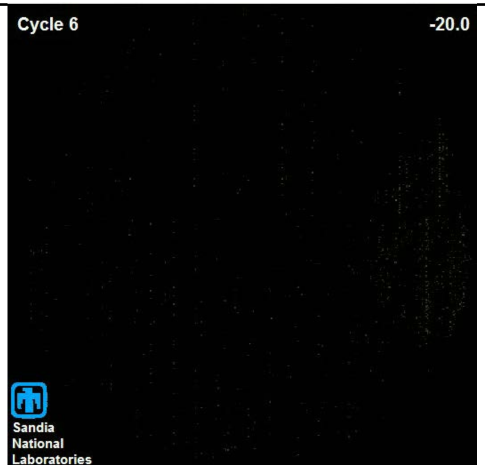
Understand fuel-lean flame ignition/propagation issues

- Flow/piston-geometry interactions
- Lean spark/pre-chamber ignition kernel growth
- Incomplete combustion
  - Fuel/tracer diagnostics

Particle Image Velocity Measurements

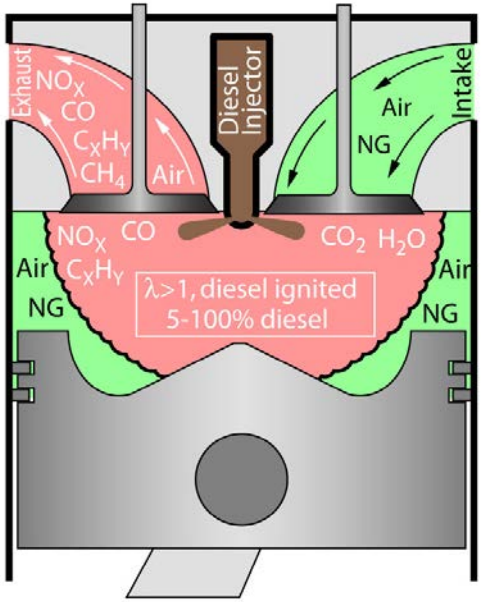


High-speed chemiluminescence imaging of RCCI with laser spark



* DOE Annual Merit Review Presentation, Miles, (2006)
** Ph.D Thesis, U. of Wisconsin, Kokjohn (2012)

Lean premixed diesel-pilot ignition challenges include combustion efficiency, aftertreatment cost



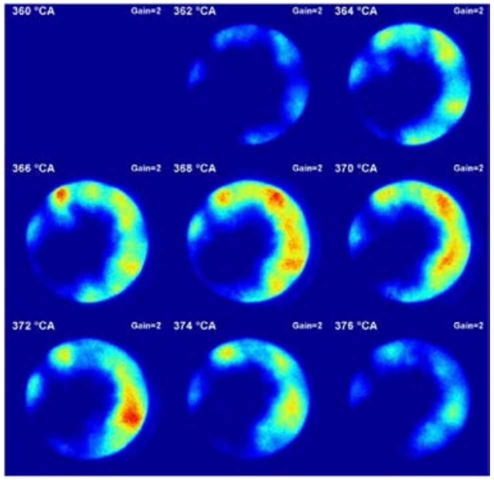
Intake	lean-premixed NG + EGR	aftertreatment for HC and CO, possibly NOx
Efficiency	~45%	high specific heat ratio, high compression ratio
NG fraction	0-95%	can run 100% diesel
Heavy-Duty	Volvo; retrofit: CAP, Hardstaff, G-Volution	
Challenges	combustion efficiency (CO, CH_4), aftertreatment costs	

Previous optical work:

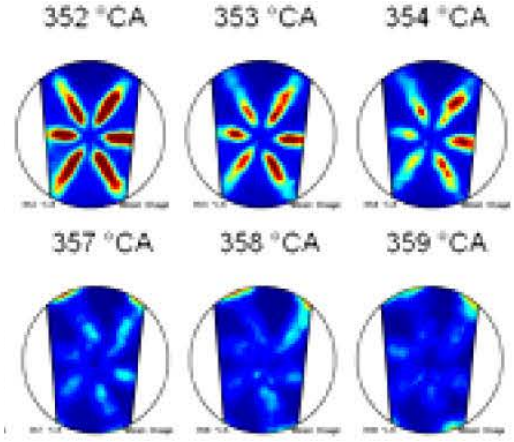
- OH Chemiluminescence shows bowl-wall ignition, incomplete combustion at center for low ϕ
- Fuel-tracer PLIF: fuel-lean at center, akin to diesel LTC PCCI

*SAE 2014-01-1313, Dronniou, Kashdan, Lecointe (IFPEN); Sauve, Soleri (Westport Innovations)

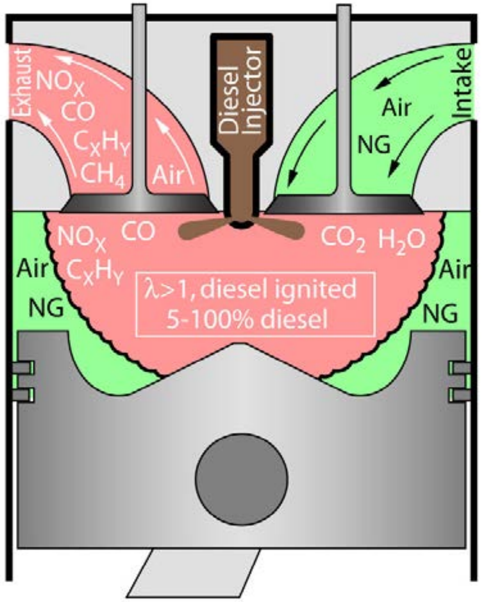
OH Chemiluminescence



Fuel-tracer PLIF



Lean premixed diesel-pilot ignition challenges include combustion efficiency, aftertreatment cost

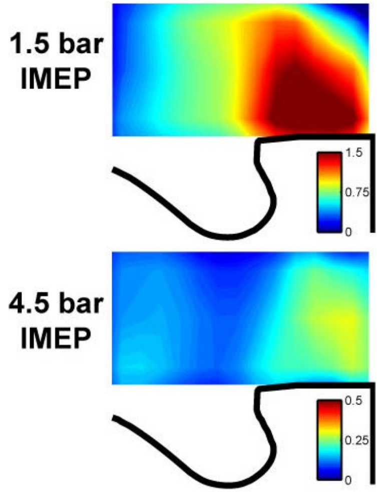


Intake	lean-premixed NG + EGR	aftertreatment for HC and CO, possibly NOx
Efficiency	~45%	high specific heat ratio, high compression ratio
NG fraction	0-95%	can run 100% diesel
Heavy-Duty	Volvo; retrofit: CAP, Hardstaff, G-Volution	
Challenges	combustion efficiency (CO, CH_4), aftertreatment costs	

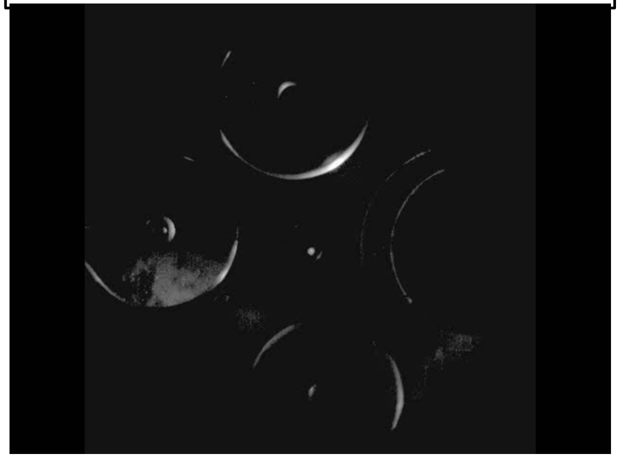
Understand fuel-lean NG w/ diesel-pilot ignition issues

- Source of CO (lean/rich)
  - Fluorescence/absorption
- Incomplete combustion
  - CH_4/Intermediates
- Source of NO (pilot comb.)

CO Fluorescence Images

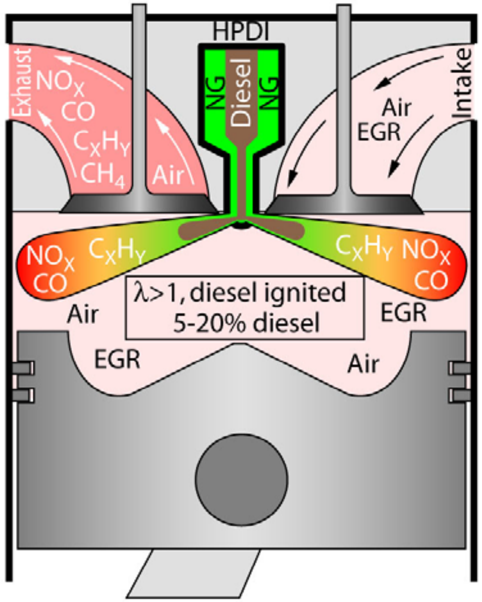


High-speed chemiluminescence of premixed gasoline + diesel



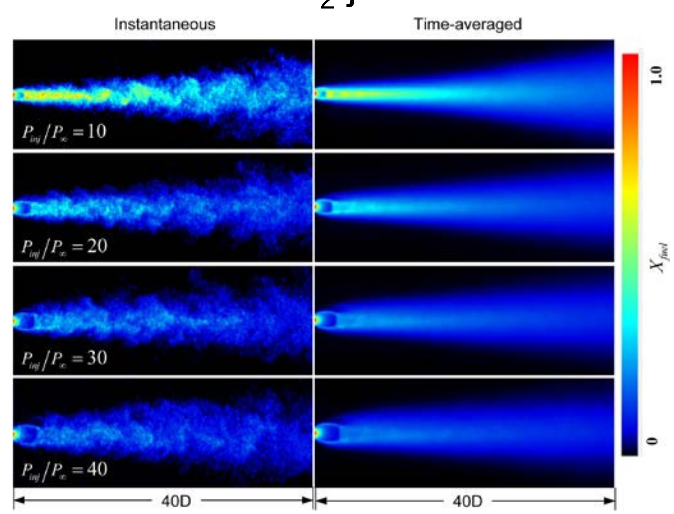
* DOE Annual Merit Review Presentation, Miles, (2010)
** Ph.D Thesis, U. of Wisconsin, Kokjohn (2012)

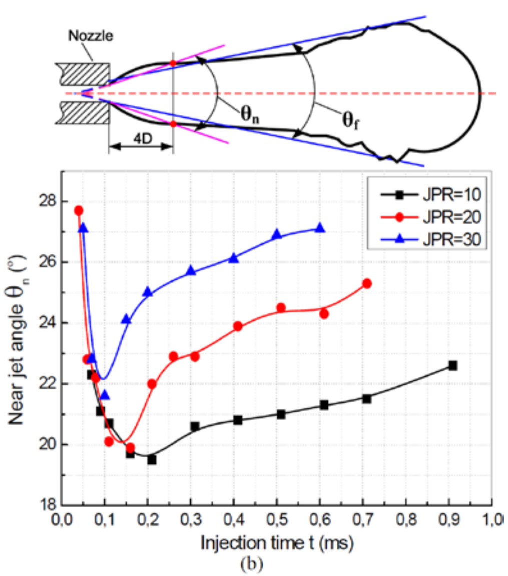
High-pressure direct injection challenges include diesel aftertreatment cost, injection interactions



Intake	air + EGR	DPF + Urea SCR (diesel)
Efficiency	~46%	high specific heat ratio, high compression ratio
NG fraction	80-95%	can't run 100% diesel
Heavy-Duty	Volvo; retrofit: CAP, Hardstaff, G-Volution	
Challenges	Diesel-like emissions, optimize dual inj.	

Acetone PLIF: N_2 jet in chamber



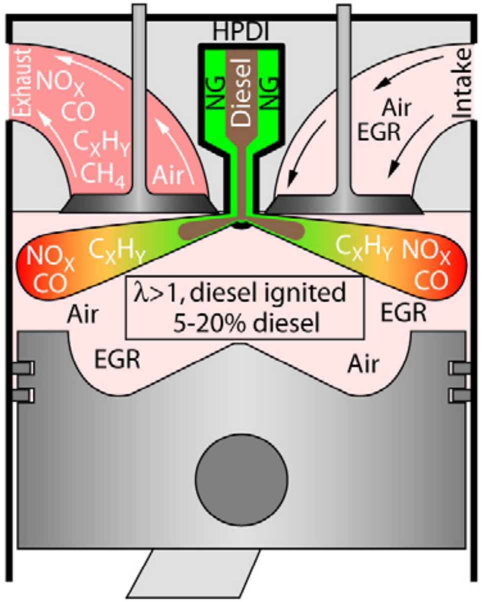


<u>Previous optical work:</u>

- PLIF shows pressure ratio affects shock structures
- Pressure ratio affects spreading angle & volume, shock-induced turbulence enhances mixing

* SAE 2014-01-1619 Yu, Vuorinen, Kaario, Sarjovaara, Larmi (Aalto)

High-pressure direct injection challenges include diesel aftertreatment cost, injection interactions



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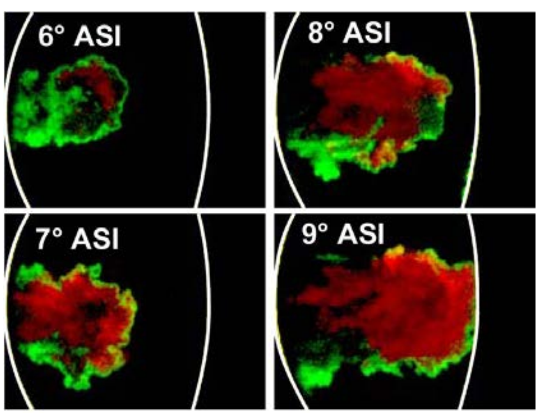
Challenges	Diesel-like emissions, optimize dual inj.	

Understand high-pressure direct-injection NG issues

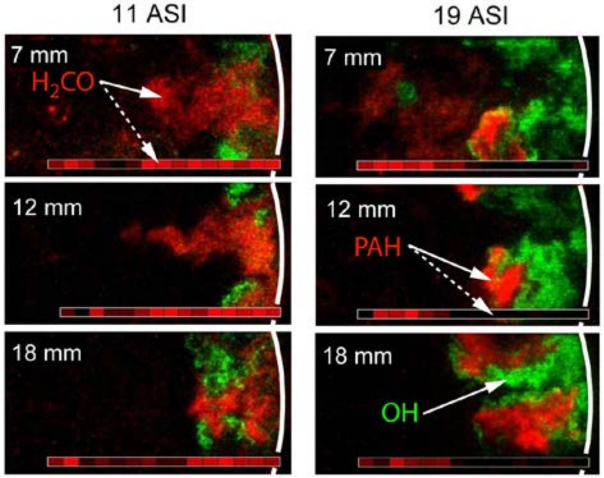
- Flame lift-off with NG and diesel pilot ignition
  - OH LIF/chemilum.
  - Soot LII / PAH LIF
- Explore LTC options
  - Partial premixing

Diesel: combined soot PLII (red) and OH PLIF (green)



* SAE 2001-01-1295, Dec and Tree (2001)

Diesel LTC: combined HCO/PAH PLIF (red) and OH PLIF (green)



** SAE 2009-01-2699, Genzale, Reitz, Musuculus

Sandia/CRF plan: convert HD optical diesel engine for NG – common platform, 4(+) comb. strategies

Three NG fuel delivery systems

1. Up to 10 bar intake-port injector
2. Up to 100 bar side-wall DI
3. Up to 600 bar Westport HPDI-style combined NG + diesel

Three ignition systems

1. Conventional spark plug
2. Diesel pilot ignition
3. Pre-chamber/spark system

Fueled with scientific-grade NG

- Certified mix with H_2 and/or C_2-C_4 species; NG recovery system

Common-platform optical engine can provide the missing science base for multiple NG strategies in reciprocating HD engines