An In-Cylinder Imaging Survey of Low-Temperature, High-Efficiency Combustion Strategies

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Chemiluminescence Movies:
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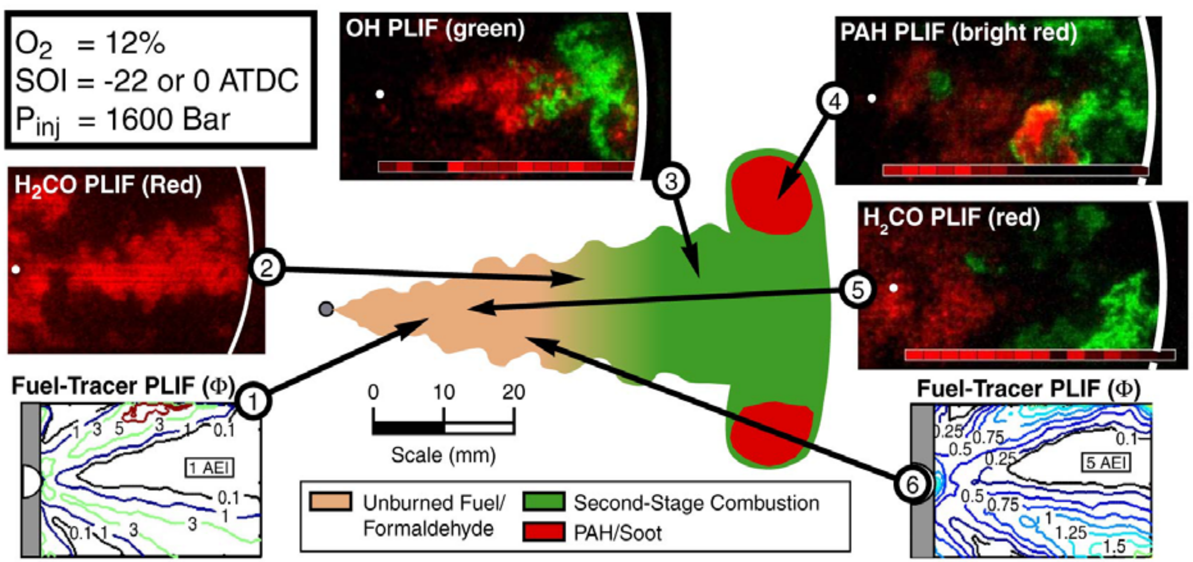
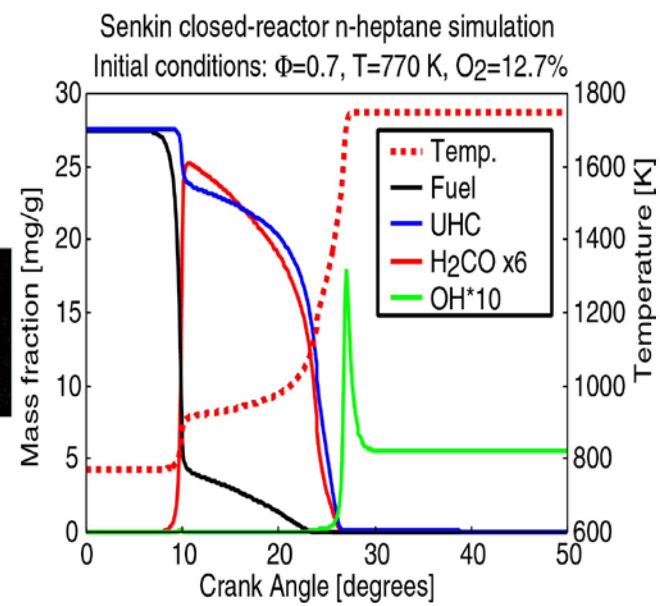
Understanding of in-cylinder LTC emissions mechanisms has improved in recent years

- Original motivation for low-temperature combustion (LTC): emissions compliance → in-cylinder
  - e.g., U.S. 2007/2010 heavy-duty diesel on-road
  - PM & NOx reductions, but UHC, CO & BSFC problems
  - Optical diagnostics & chemical kinetics lend insight



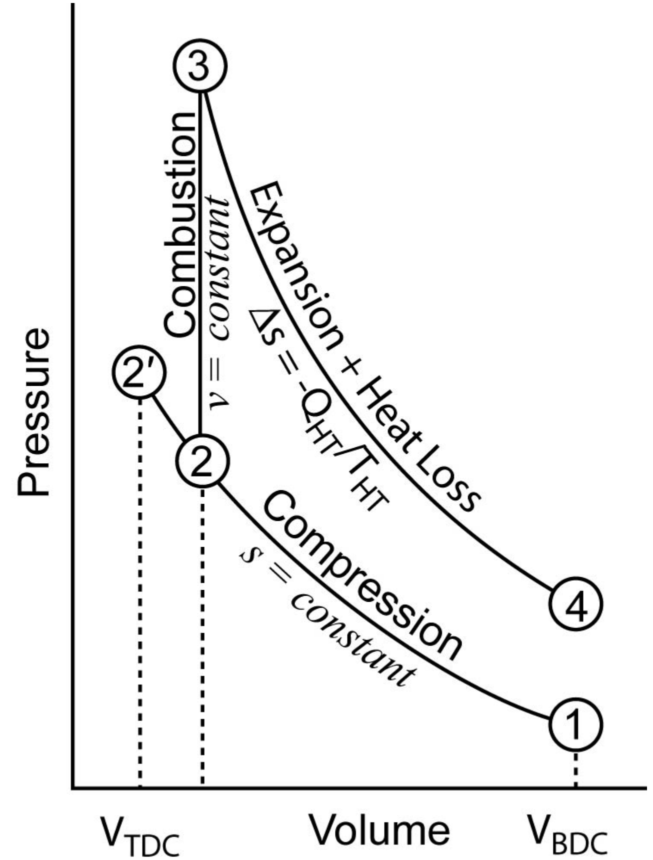


Thermodynamic analysis: quantitative efficiency comparisons among operating strategies

- Recently, some LTC strategies have demonstrated improvements in both emissions and efficiency
  - HCCI, RCCI: 50%+ ind. efficiency at 2010 PM/NOx
- Can we quantify contributions of r_c, ϕ, EGR, etc. to efficiency among engines using thermodynamics?
  - Gross, indicated fuel-conversion efficiency: $\eta_{fc,i,g} = f(r_c, \phi, EGR, \ldots)$
  - Differential efficiency: $d\eta_{fc,i,g} = \frac{\partial \eta}{\partial r_c} dr_c + \frac{\partial \eta}{\partial \phi} d\phi + \frac{\partial EGR}{\partial EGR} dEGR + \ldots$
  - Integration gives: $\Delta\eta_{1\to 2} = \Delta\eta_{r_c} + \Delta\eta_{\phi} + \Delta\eta_{EGR} + \ldots$
  - Individual contributions are path dependent
    - Parameterize: $r_c = r_{c,1} + \alpha(r_{c,2} - r_{c,1}),\ \phi = \phi_1 + \alpha(\phi_2 - \phi_1), \ldots$
    - Use linear variation: $\alpha = 0 \to 1$

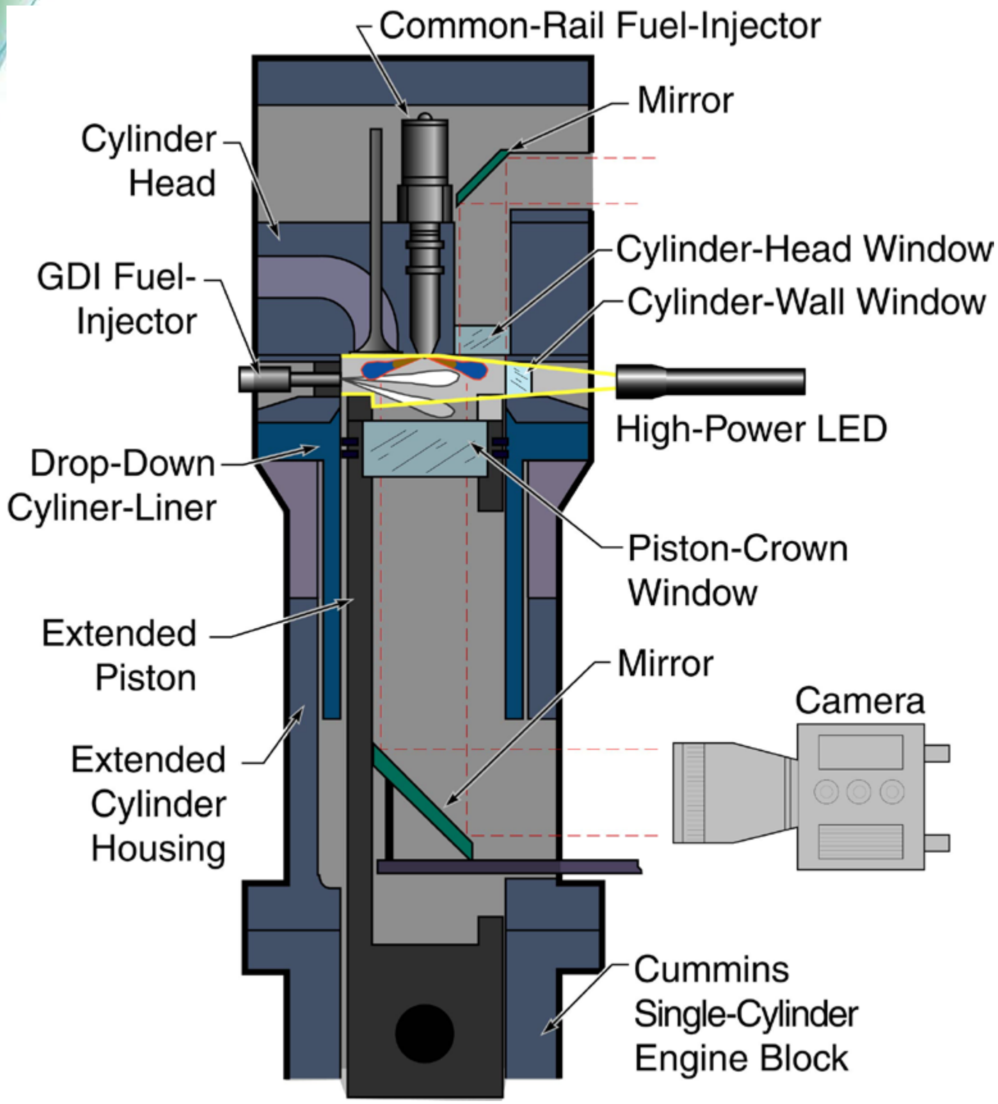
"Simple-as-possible" four-state model for thermodynamic efficiency analysis

- C_p & C_v vary with T & gas composition
- 1→2: Isentropic compression to reduced r_c (after TDC)
  - Accounts for combustion phasing & finite duration of combustion
  - θ_{comb} approximately at CA50
- 2→3: Constant-volume combustion
  - Account for combustion efficiency
- 3→4: Expansion with heat transfer (HT)
  - Use $\Delta S_{3\rightarrow 4} = \int \frac{dQ_{HT}}{T} = \frac{-\Delta Q_{HT}}{T_{HT}}$
  - T_{HT} gives same ΔS as integral
  - θ_{HT} approximately at HT centroid



Cautions!:
1. Model is for analysis, not prediction
2. Results depend on assumptions, inputs, and path between engine configurations (not universal!)

Sandia optical heavy duty engine with dual-fuel injection

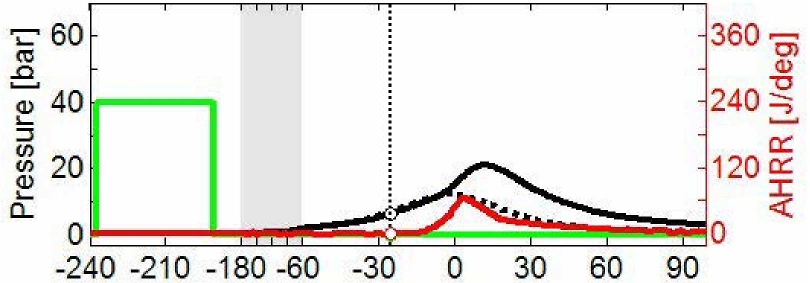


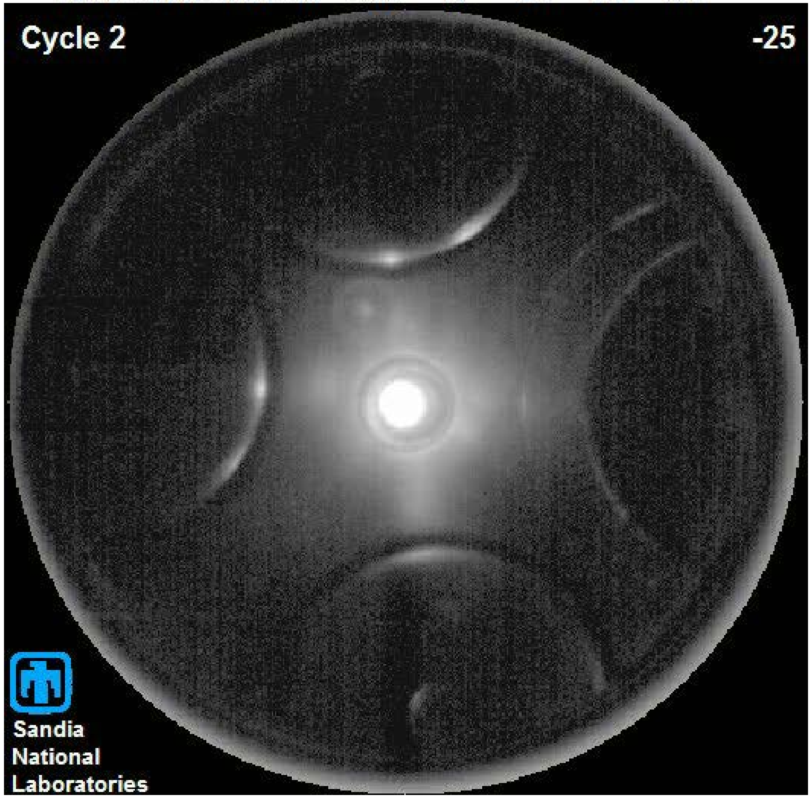
- Bosch GDI (100 bar) mounted in place of side-window
  - Premixed gasoline-like fuel (SI, HCCI, RCCI)
- 8-hole production Cummins XPI common-rail fuel injector (300-1600 bar) in cylinder head
  - Direct inj. of diesel-like fuel (CIDI, RCCI, PCI, MK)
- Sprays illuminated using CW high-power LED white-light source through side-windows

Conventional spark ignition (gasoline): 33.6% gross indicated efficiency

$r_{c,geom}$	10
θ_{comb} (r_c)	15° (8.4)
ϕ_{global}	1
η_{comb}	97%
Q_{HT}/LHV	25%?
θ_{HT} (T_{HT})	25°? (2815 K)
Intake O_2	21%
$\eta_{fc,i,g}$	33.6%

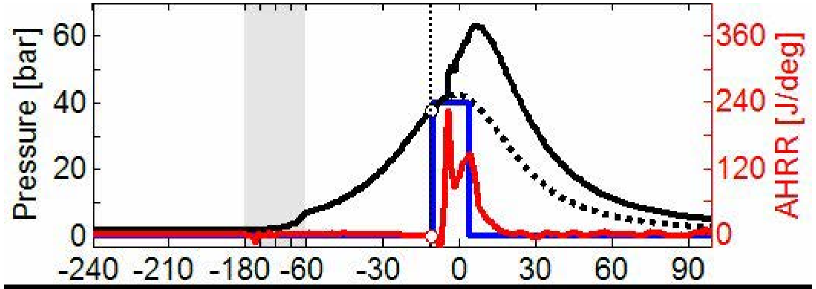
Q_{HT}/LHV and θ_{HT} are highly uncertain, with order-of-magnitude variations in predictions among global correlations (Caton, IC10, 2011 US Nat. Comb. M.)





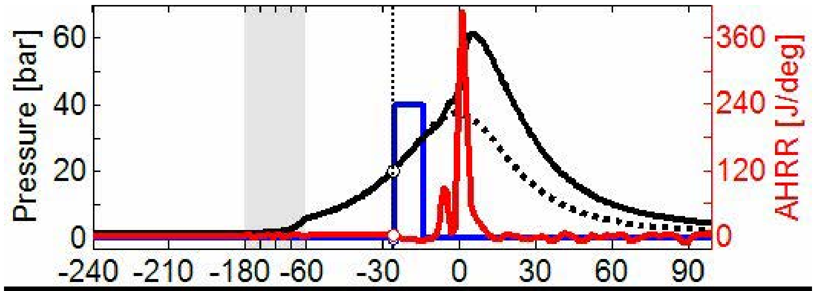
CIDI 11.8 %-pt. efficiency gain over SI: r_c, ϕ, & comb. phasing (+heat transfer?)

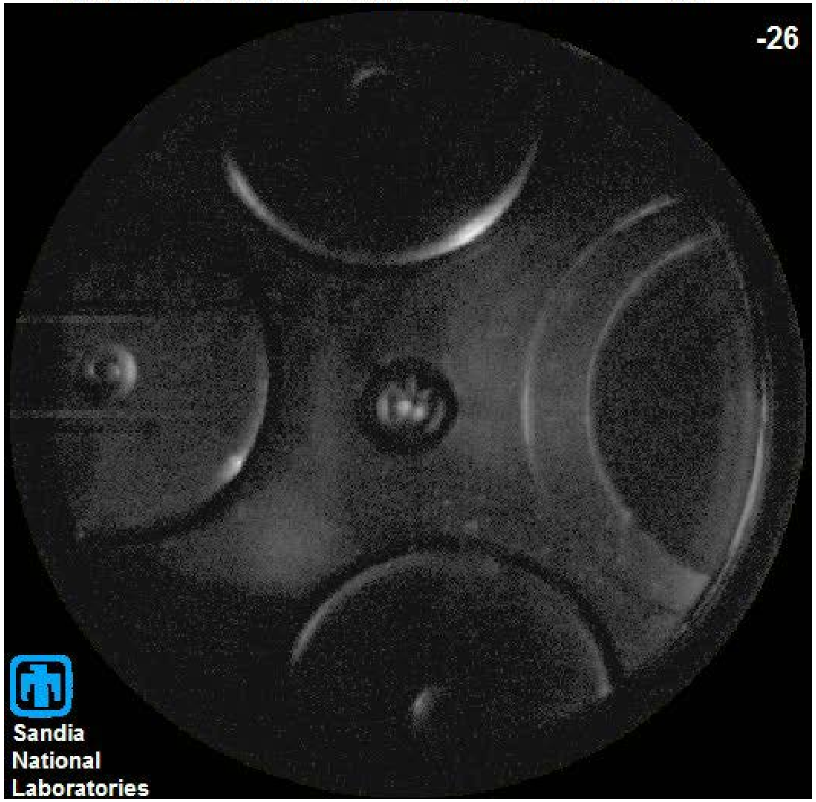
	SI	CIDI	$\Delta\eta_{fc,I,g}$
$r_{c,geom}$	10	16	4.9%
θ_{comb}	15°	10°	1.8%
ϕ_{global}	1	0.5	2.1%
Premix	100%	0%	-1.9%
$\phi_{DI,TDC}$	(1)	1	-
η_{comb}	96%	99%	0.7%
Q_{HT}/LHV	25%?	16%?	4.2%?
θ_{HT}	25°?	25°?	-
Intake O_2	21%	21%	-
$\eta_{fc,i,g}$	33.6%	45.4%	11.8%



PCI efficiency similar to conventional CIDI, η_{comb} penalty is significant

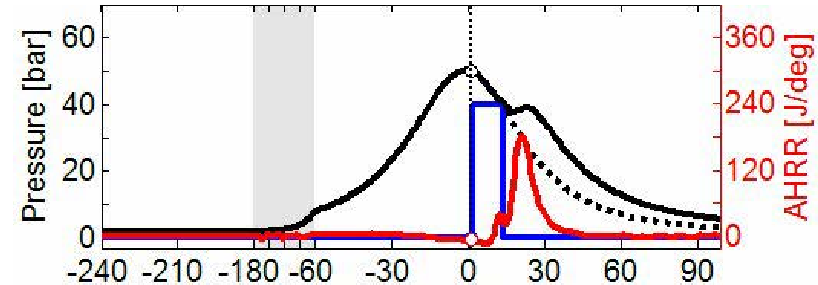
	CIDI	PCI	$\Delta\eta_{fc,I,g}$
$r_{c,geom}$	16	14	-1.5%
θ_{comb}	10°	5°	1.2%
ϕ_{global}	0.5	0.4	0.4%
Premix	0%	25%	0.8%
$\phi_{DI,TDC}$	1	.7	0.9%
η_{comb}	99%	95%	-1.7%
Q_{HT}/LHV	16%?	14%?	0.9%
θ_{HT}	25°?	25°?	-
Intake O_2	21%	15%	0.8%
T_{Intake}	30 °C	60 °C	-0.3%
$\eta_{fc,i,g}$	45.4%	46.9%	1.5%





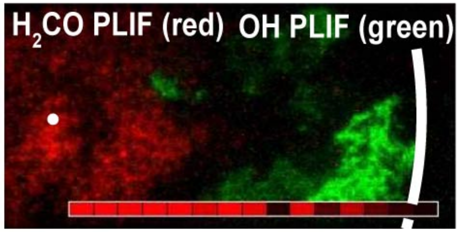
MK efficiency similar to conventional CIDI, η_{comb} penalty is significant

	CIDI	MK	$\Delta\eta_{fc,I,g}$
$r_{c,geom}$	16	16	-
θ_{comb}	10°	15°	-1.9%
ϕ_{global}	0.5	0.4	0.3%
Premix	0%	25%	0.8
$\phi_{DI,TDC}$	1	.9	0.4
η_{comb}	99%	95%	-1.7%
Q_{HT}/LHV	16%?	14%?	0.9%?
θ_{HT}	25°?	30°?	0.4%
Intake O_2	21%	15%	0.9%
T_{Intake}	30 °C	60 °C	-0.3%
$\eta_{fc,i,g}$	45.4%	45.2%	-0.2%

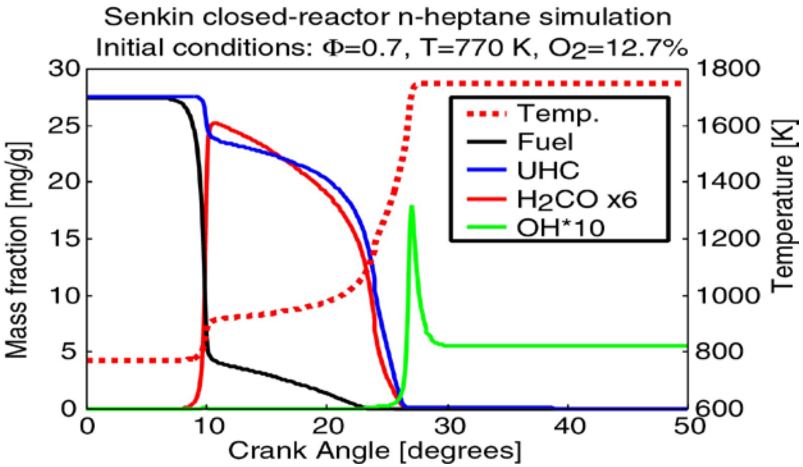


PCI, MK combustion efficiency: Post-injections can reduce UHC 20-25%

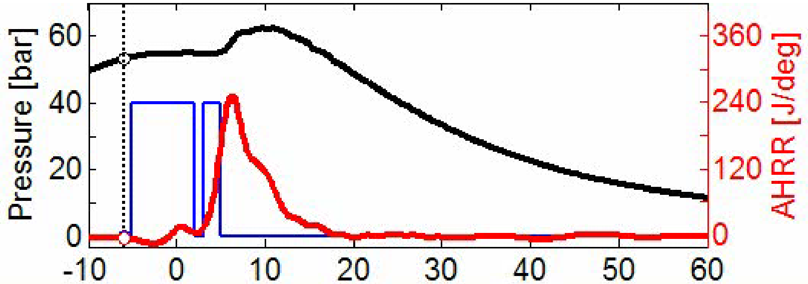
- Optical diagnostics: late-cycle formaldehyde (red) near injector

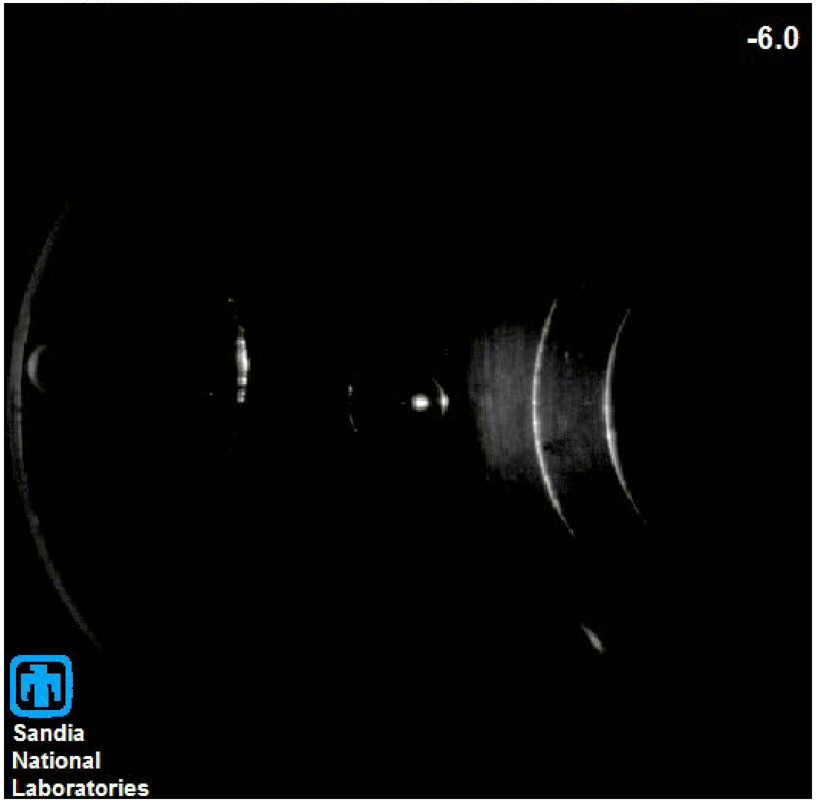


- Chemical kinetics: cause=overmixing



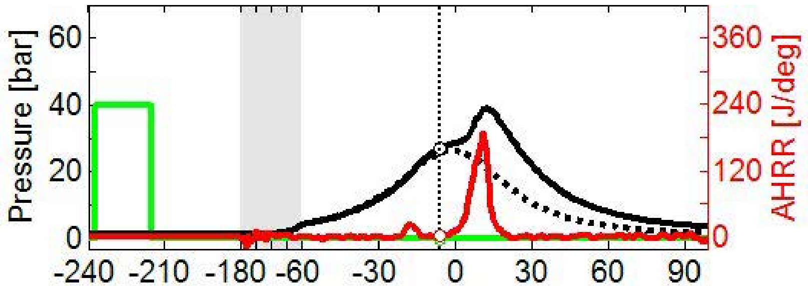
- Post-injections: enrich residual mixtures, UHC ↓20-25% at same load

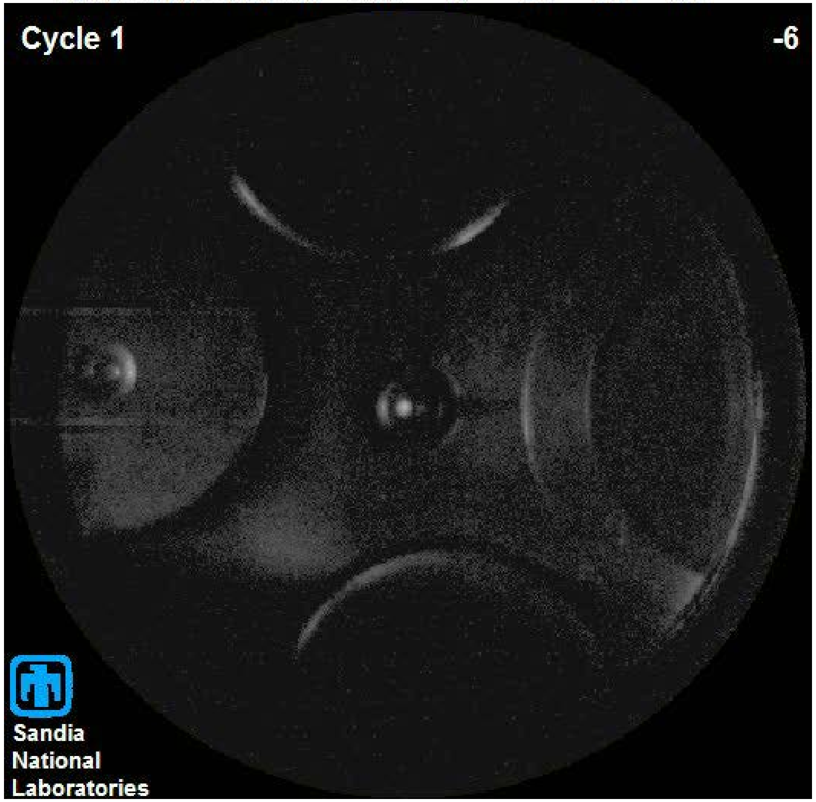




HCCI gains: uniformly low T & comb. phasing (+heat trans.?); loss from r_c

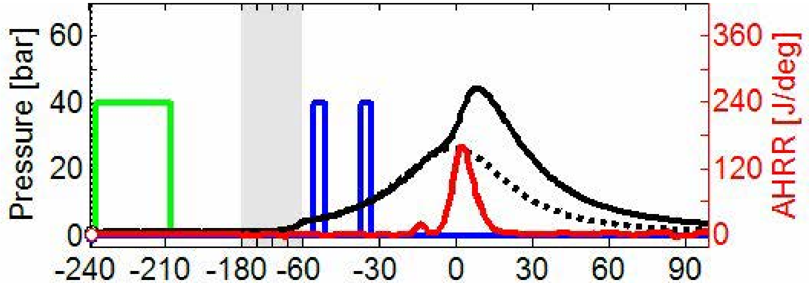
	CIDI	HCCI	$\Delta\eta_{fc,l,g}$
$r_{c,geom}$	16	14	-1.5%
θ_{comb}	10°	5°	1.2%
ϕ_{global}	0.5	0.5	-
Premix	0%	100%	3.5%
$\phi_{DI,TDC}$	1	-	-
η_{comb}	99%	97%	-0.9%
Q_{HT}/LHV	16%?	12%?	1.9%?
θ_{HT}	25°?	30°?	0.4%
Intake O_2	21%	18%	0.3%
T_{Intake}	30 °C	60 °C	-0.3%
$\eta_{fc,i,g}$	45.4%	50%	4.6%





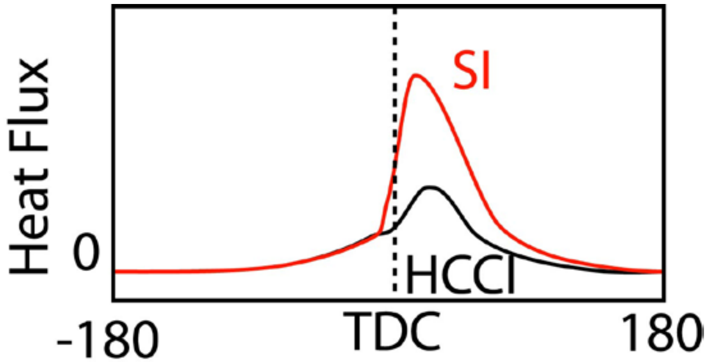
RCCI gains from uniformly low T & comb. phasing (+heat transfer?)

	CIDI	RCCI	$\Delta\eta_{fc,l,g}$
$r_{c,geom}$	16	16	-
θ_{comb}	10°	5°	1.3%
ϕ_{global}	0.5	0.4	0.6%
DI_{TDC}	0%	80%	2.3%
$\phi_{DI,TDC}$	1	.5	1.3%
η_{comb}	99%	97%	-0.9%
Q_{HT}/LHV	16%?	12%?	1.8%?
θ_{HT}	25°?	30°?	0.4%
Intake O_2	21%	21%	-
T_{Intake}	30 °C	30 °C	-
$\eta_{fc,i,g}$	45.4%	52.2%	6.8%

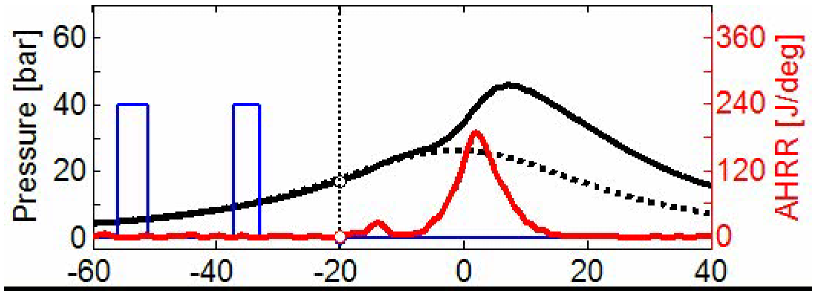


Artificial ignition shows flame propagation potential in RCCI

- Heat flux measurements (SAE 2004-01-2996, Chang et al): different heat transfer for flame propagation (SI) and distributed auto-ignition (HCCI)



- RCCI might support both, so heat transfer (efficiency) among RCCI engines may depend on regime
- Artificial ignition (by laser) shows some RCCI regions can support flame propagation



Conclusions: Thermo. model shows LTC efficiency gains from T uniformity, comb. phasing (and HT?)

- Simple 4-state thermodynamic model provides quantitative comparisons among engine combustion strategies
  - Results depend on assumptions and path: **Results are not universal!**
- Model: reducing comb. T for emissions can also improve efficiency
  - HCCI & RCCI gain from uniformly low T, comb. phasing, (& HT?)
- Heat transfer uncertainty & efficiency effects are considerable
  - Effects of flames, sprays, sequential ignition, etc.