Dilute Clean Diesel Combustion Achieves Low Emissions and High Efficiency While Avoiding Control Problems of HCCI

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Motivation

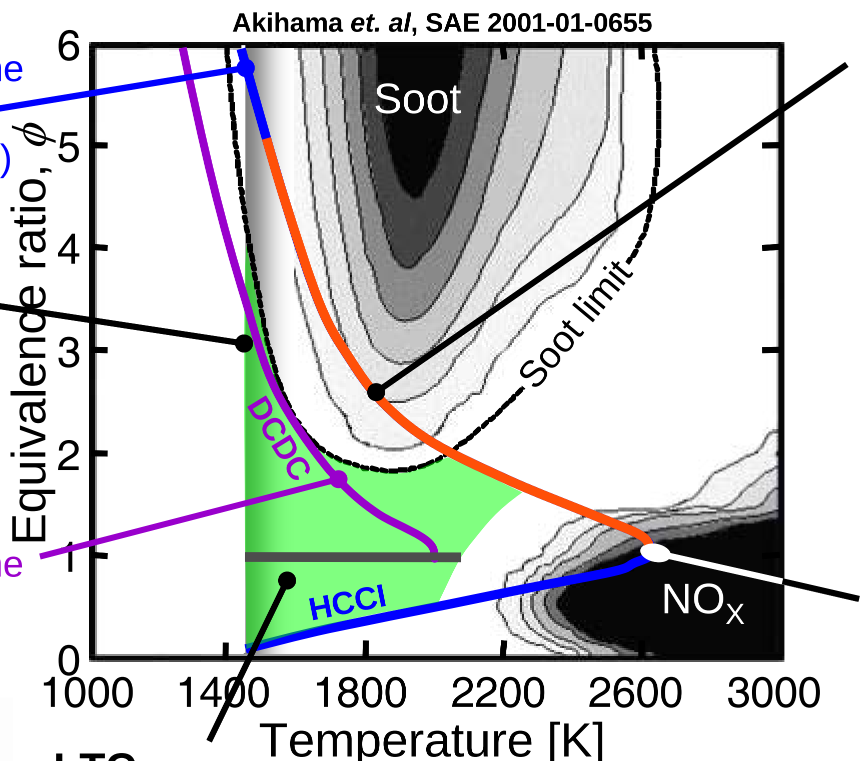
- **US 2010 heavy-duty emissions regulations are driving development of cleaner engine technologies**
  - **In-cylinder emissions control is desirable to engine OEMs → avoids potentially costly aftertreatment systems**
- **High efficiency is critical from many perspectives**
  - **Fuel economy: strongly impacts engine marketability**
  - **Energy security: petroleum imports affect national security**
  - **Greenhouse-gas emissions: global importance will grow**
- **One promising strategy is Low-Temperature Combustion (LTC)**
  - **HCCI is one way to achieve LTC**
    - Subject of much research
    - Presents some significant technical challenges
  - **There are other ways to achieve LTC**
    - Dilute Clean Diesel Combustion (DCDC)

Graphical Summary of SI, CI, and LTC Modes

Adiabatic flame temperature in air (21% O_2)

CO to CO_2 conversion diminishes

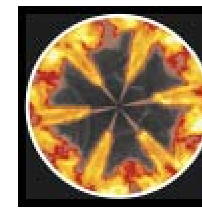
Adiabatic flame temperature 10% O_2



DCDC

Diesel (CI) combustion

- Controlled heat release (mixing)
- Controlled combustion timing
- Wide load range
- High efficiency (relative to SI)
- **NO_x and PM emissions**



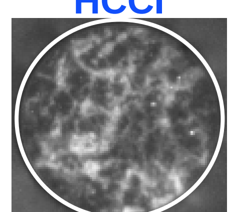
Spark ignition (SI) combustion

- Controlled heat release (flame propagation)
- Controlled combustion timing
- Wide load range
- Three-way catalyst
- **Low efficiency** (relative to diesel)

LTC

- High efficiency (high CR, no throttle)
- Low NO_x and PM emissions
- **Load range?**
- **Combustion timing?**
- **Heat release rate?**
- **Transient control?**
- **Fuel?**

HCCI

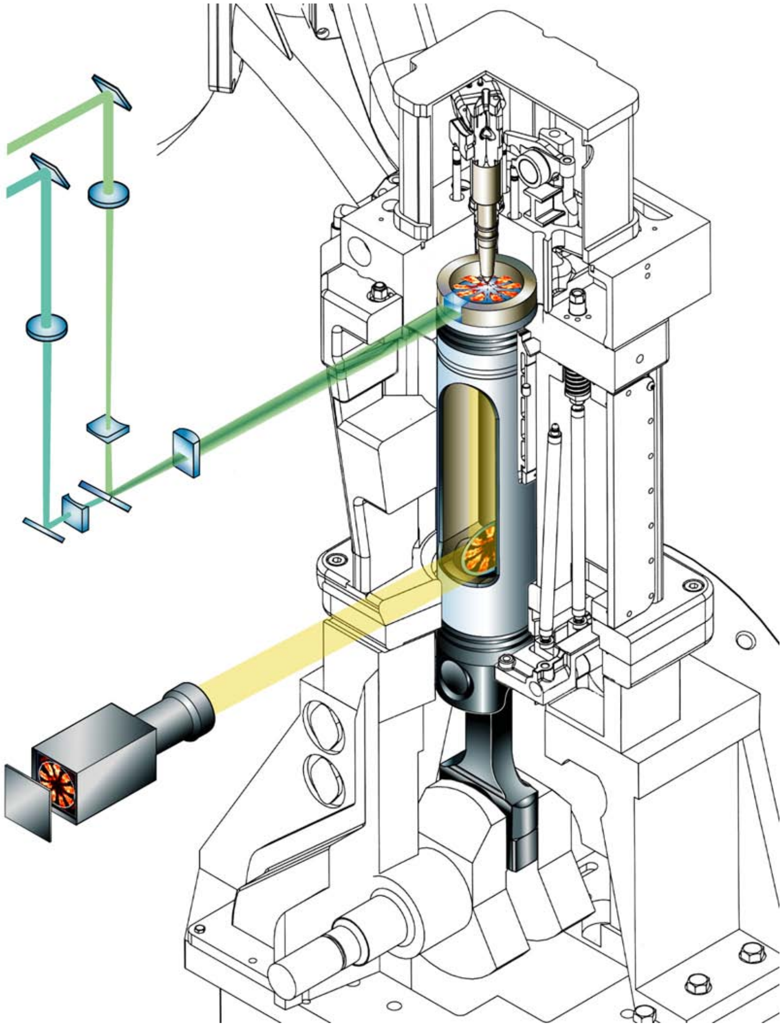


How are DCDC and HCCI Different?

- **HCCI → premixed, $\phi \leq 1$, volumetric reaction**
  - **Kinetics, temperature/mixture fields control combustion timing**
  - **Mixture preparation: early injection or late injection with high swirl**
  - **Potential limitations**
    - Difficult to control combustion timing
    - Knock and high NO_x (and PM) emissions at high loads
    - Liquid fuel impingement on in-cylinder surfaces
    - Incomplete combustion at light loads (misfire, high UHC and CO)
- **DCDC → non-premixed, $\phi \geq 1$, mixing-controlled reaction**
  - **DCDC = Traditional diesel + high EGR + low-sooting fuel and/or enhanced mixing**
  - **Injection timing controls combustion timing**
  - **Potential limitations**
    - Requires high EGR levels
    - May hit “smoke limit” with EGR before attaining req’d NO_x emissions

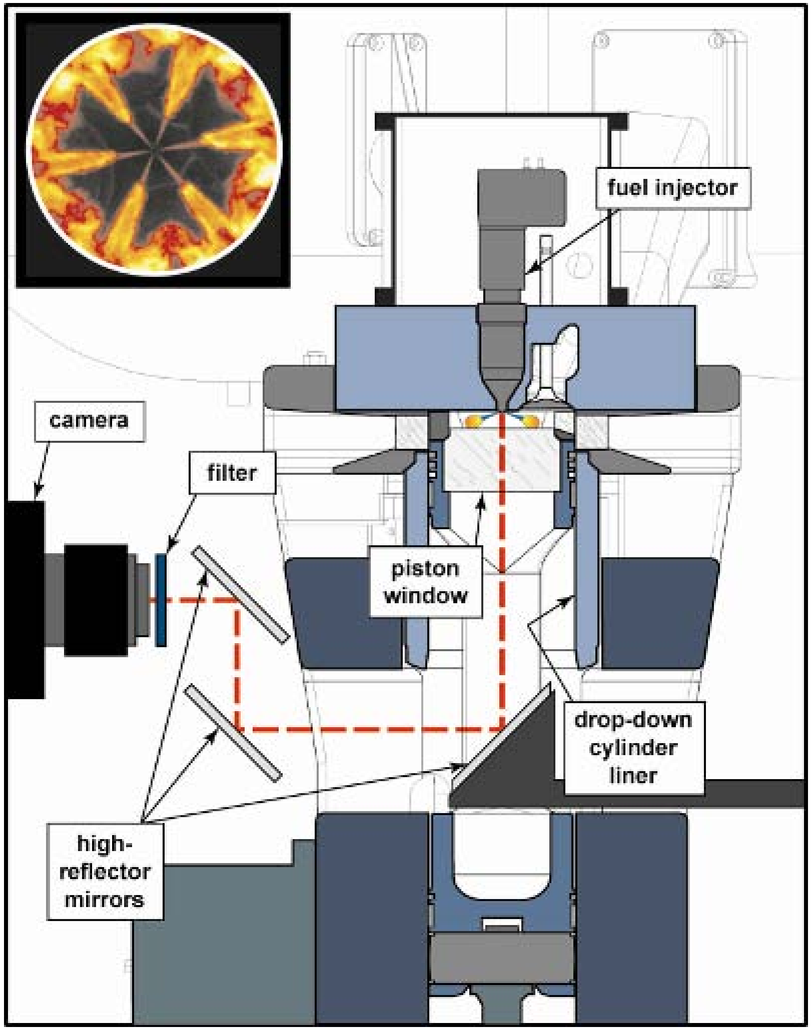
Approach

- Study DCDC using highly oxy-genated fuel
  - Fuel is neat diethylene glycol diethyl ether, DGE ($C_8H_{18}O_3$)
  - Helps avoid "soot peninsula" on ϕ-T plot
  - Short ignition delay
- Use optical engine and in-cylinder diagnostics to see how combustion processes change with dilution
- Use engine-out emissions measurements to link trends with results from metal engines



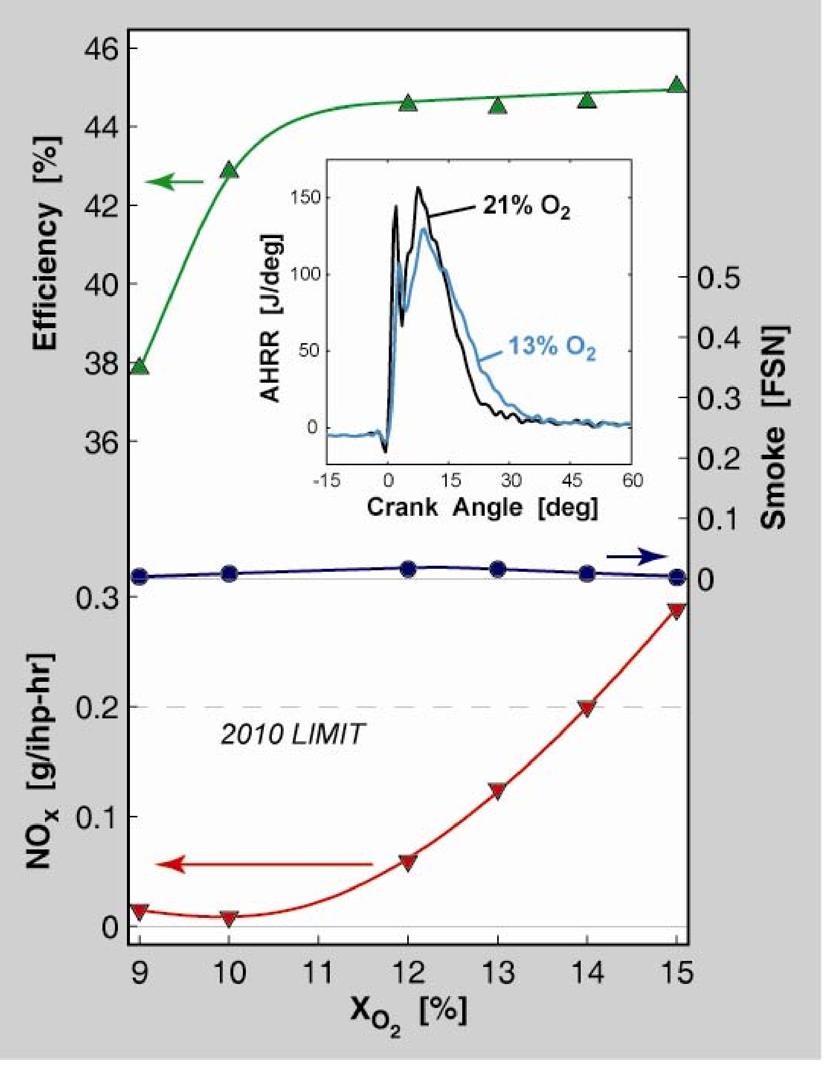
Optical Engine Specifications and Schematic

Research engine	1-cyl. Cat 3176
Cycle	4-stroke CIDI
Valves per cylinder	4
Bore	125 mm
Stroke	140 mm
Intake valve open	32° BTDC exhaust
Intake valve close	153° BTDC compr.
Exhaust valve open	116° ATDC compr.
Exhaust valve close	11° ATDC exhaust
Conn. rod length	225 mm
Conn. rod offset	None
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
Compression ratio	11.3:1
Simulated compr. ratio	16.0:1



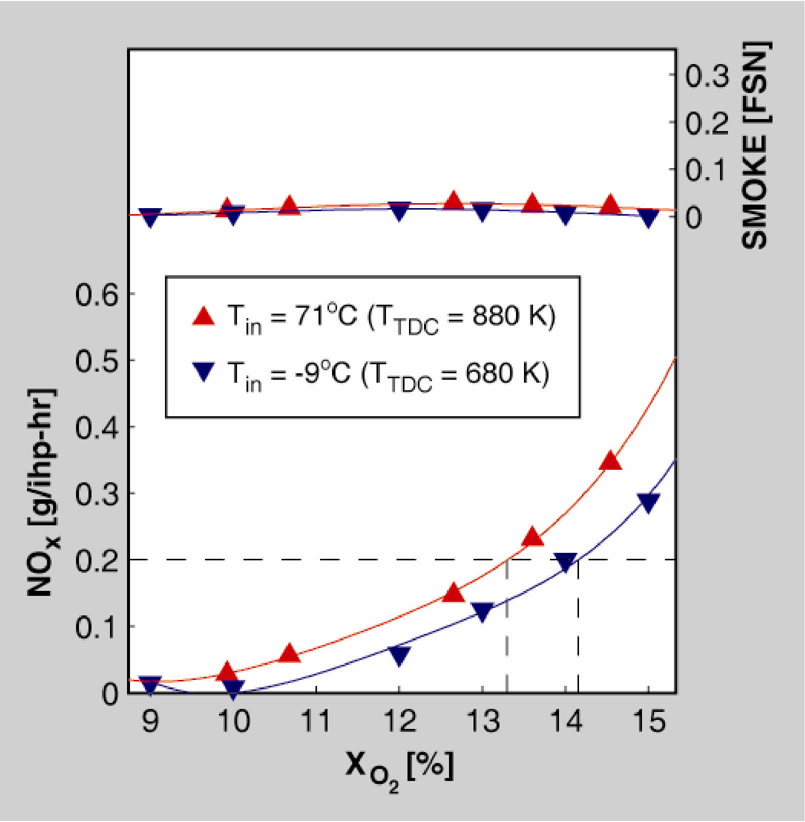
DCDC Achieves Low Emissions and High Efficiency Simultaneously

- **Operating conditions**
  - **DGE fuel**
  - **1200 rpm, 7-bar IMEP**
  - **Steady-state operation**
  - **-9°C, 1.4 bar intake**
  - **EGR simulated by N_2 dilution**
- **Benefits**
  - **NO_x below 2010 levels for 14% intake O_2 and lower**
  - **Smoke ≈ 0 for all dilution levels**
  - **NO_x/PM aftertreatm't not req'd**
  - **High efficiency for ~11% intake O_2 and higher**
  - **Simple control of ign. timing**
  - **Reduced pressure-rise rate**

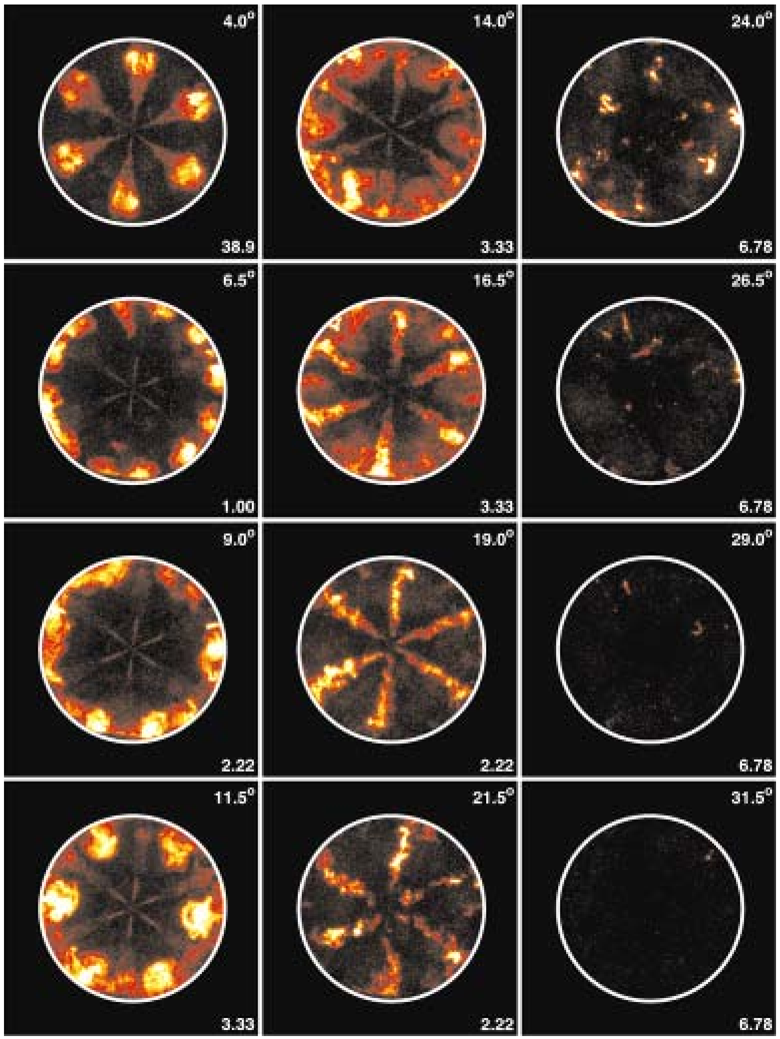


DCDC Successful at Higher Intake Temperatures and Engine Loads

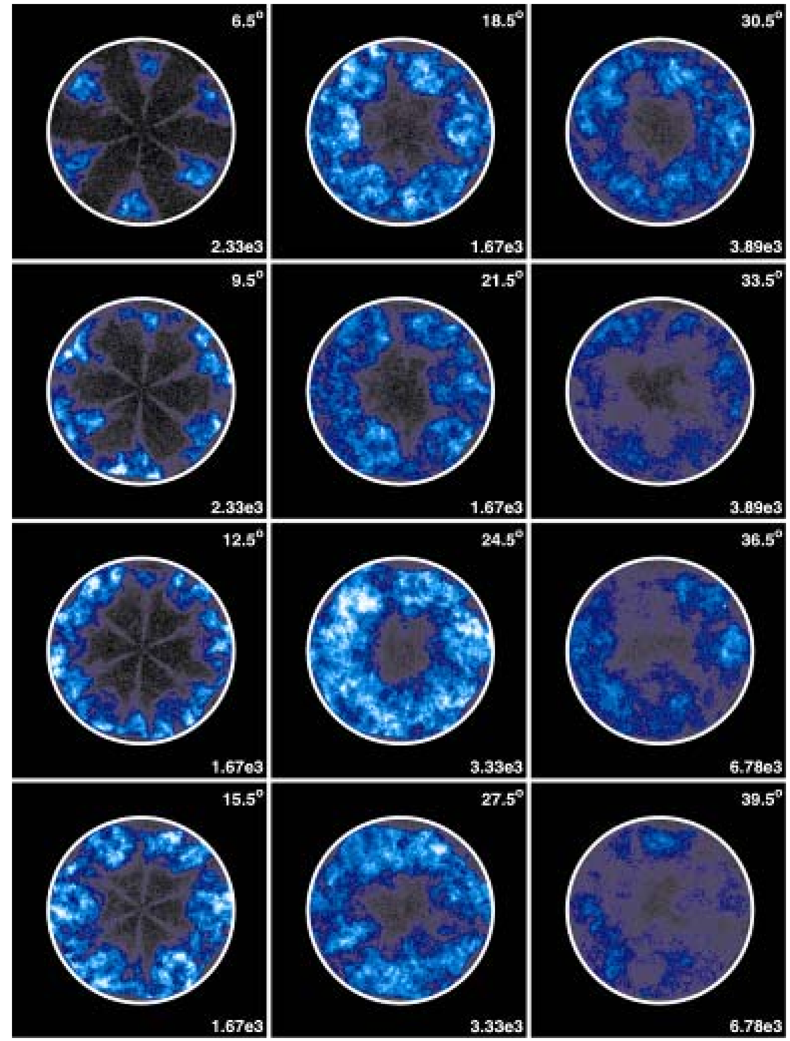
- **As intake temperature ↑ to 71°C**
  - **NO_x emissions ↑**
  - **2010 emissions achieved for ~13% intake O_2 vs. 14% O_2 at T_{in} = -9°C**
  - **Smoke remains ≈ 0**
- **High-load operation demonstrated in optical engine**
  - **18-bar IMEP (2/3 load)**
  - **0.09 g/ihp-hr NO_x**
  - **0.26 FSN smoke**
  - **Load and efficiency limited by peak cylinder pressure capability of optical engine**



Natural Luminosity Imaging of Undiluted and Highly Dilute Combustion



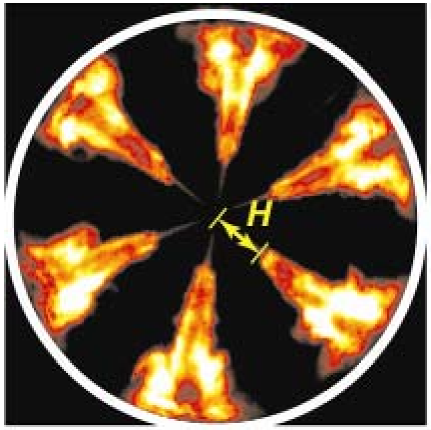
UNDILUTED



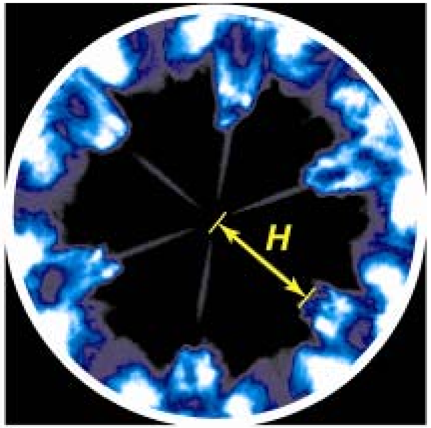
9% INTAKE O_2

Observations: DCDC In-Cylinder Processes

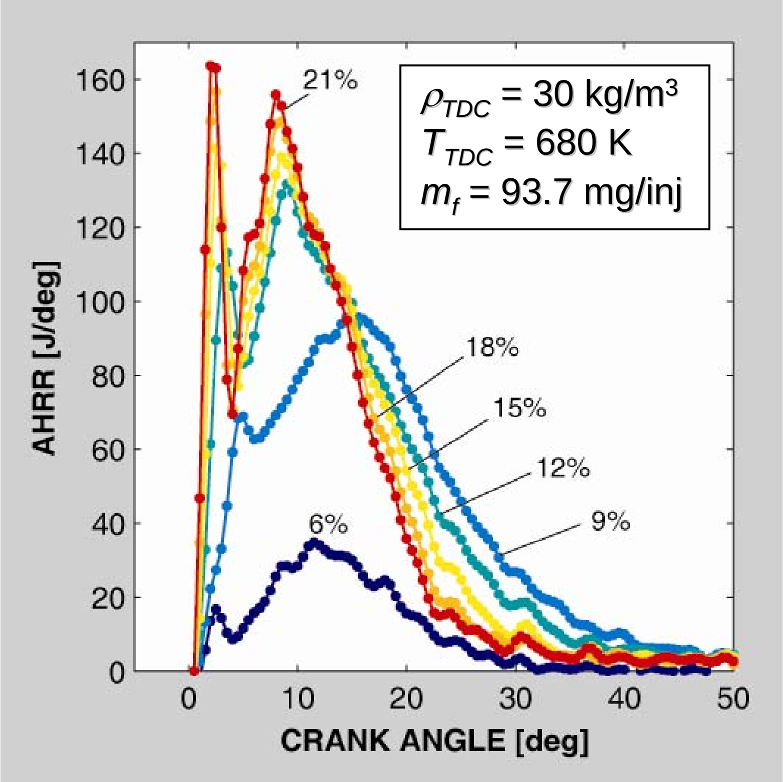
- **Diffuse combustion, ~1000X lower natural luminosity signal**
- **Longer combustion duration, lower peak heat-release rate**
- **Mixture at lift-off length is still rich but no soot is formed**



21% O_2
$\phi_\Omega(H) = 2.7$

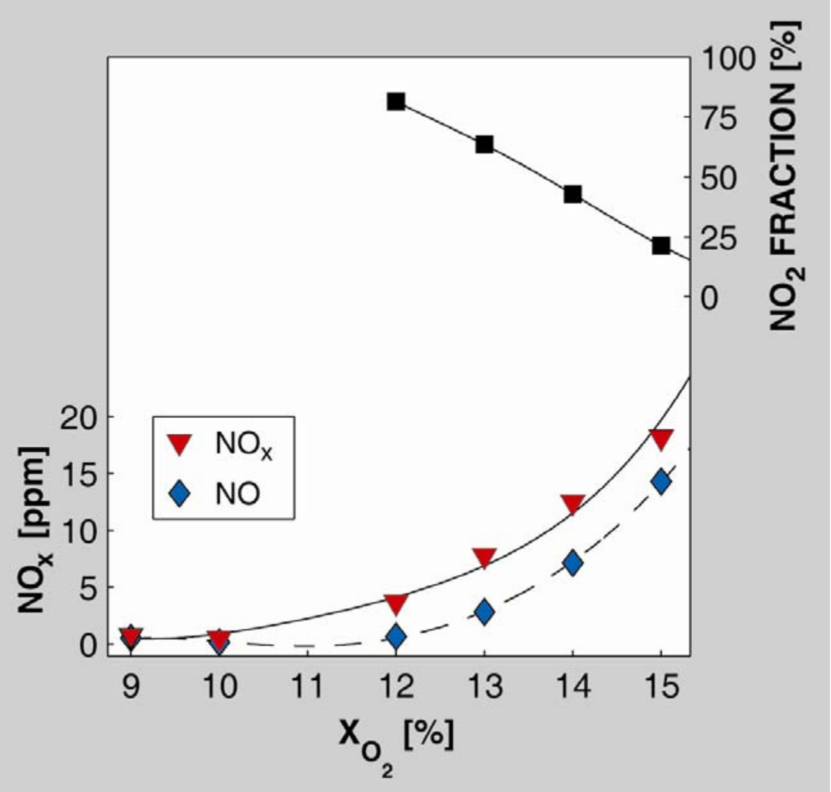


9% O_2
$\phi_\Omega(H) = 2.9$



NO / NO_2 Partitioning with DCDC

- **NO falls to zero more quickly than NO_x as dilution is increased**
- **Majority of NO_x is NO_2 for intake O_2 mole fractions below ~14%**



Summary and Conclusions

- DCDC may be an attractive LTC alternative to HCCI
  - Low emissions of NO_x and PM
  - High efficiency over broad load range
  - Simple control of ignition timing
  - Reduced pressure-rise rates
  - High-load capability
- Observations at low intake-O_2 concentrations
  - Diffuse combustion with negligible soot incandescence
  - Soot formation suppressed by low flame temperatures
  - NO_2 can comprise majority of NO_x emissions
- Remaining challenges for DCDC
  - Requires high EGR levels for low emissions
  - Requires high boost levels for high power density
  - Achievable with realistic fuels?

Future Work and References

- **Future work**
  - **Investigate suitability of broad classes of fuels for DCDC operation**
    - Fischer-Tropsch paraffins, biodiesel, ethers, middle distillates
  - **Upgrade optical engine for higher cylinder pressure capability**
  - **DOE HECC collaborative research with Caterpillar, ExxonMobil, IAV Automotive**
- **References**
  - **For more information**
    - Akihama *et al*.: SAE 2001-01-0655
    - EPA patents: US 6,301,888 (2001); 6,470,682 (2002); 6,651,432 (2003)
    - Pickett and Siebers: SAE 2004-01-1399
    - Upatnieks, Mueller and Martin: SAE 2005-01-0363, 2005-01-2088
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