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Ducted Fuel Injection: A New Approach for Lowering Soot Emissions from Direct-Injection Engines

Charles J. Mueller, Christopher W. Nilsen, Daniel J. Ruth, Ryan K. Gehmlich, Lyle M. Pickett, and Scott A. Skeen
Sandia National Laboratories, Engine Combustion Research Department

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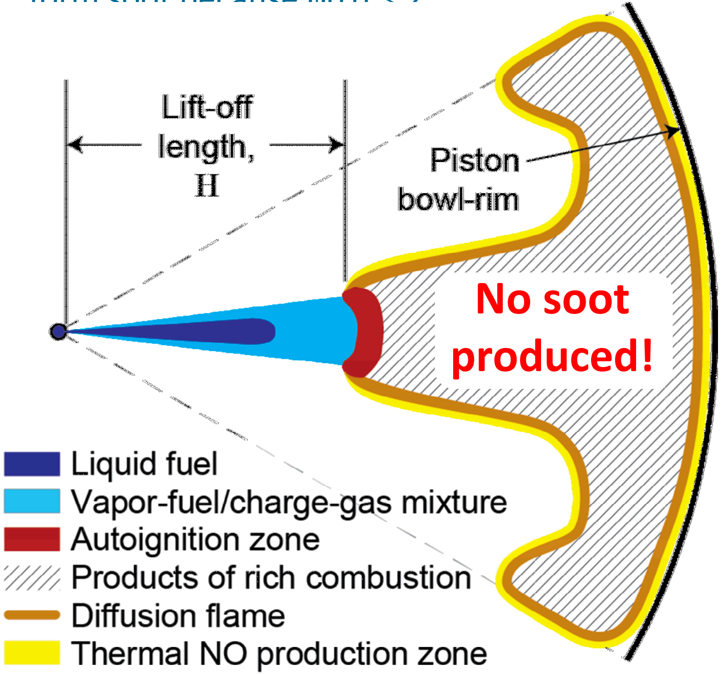
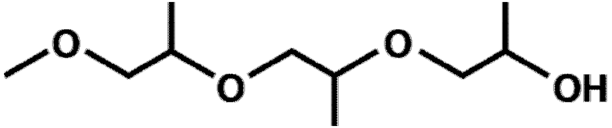
There is a mixing-controlled CI combustion mode that doesn't produce soot: LLFC.

- **Smaller, less-expensive DPF required**
  - Fewer regenerations, lower efficiency penalty
- **Soot/NO_x trade-off is broken**
  - Facilitates NO_x control via dilution
- **High efficiency of the CI cycle is maintained**
  - Low HC, CO, and CO_2 emissions
- **Fuel flexibility of the CI cycle is maintained**
  - Oxygenated renewable fuels are beneficial
- **Ign. timing easily controlled by inj. timing**
- **Potential for lower noise**

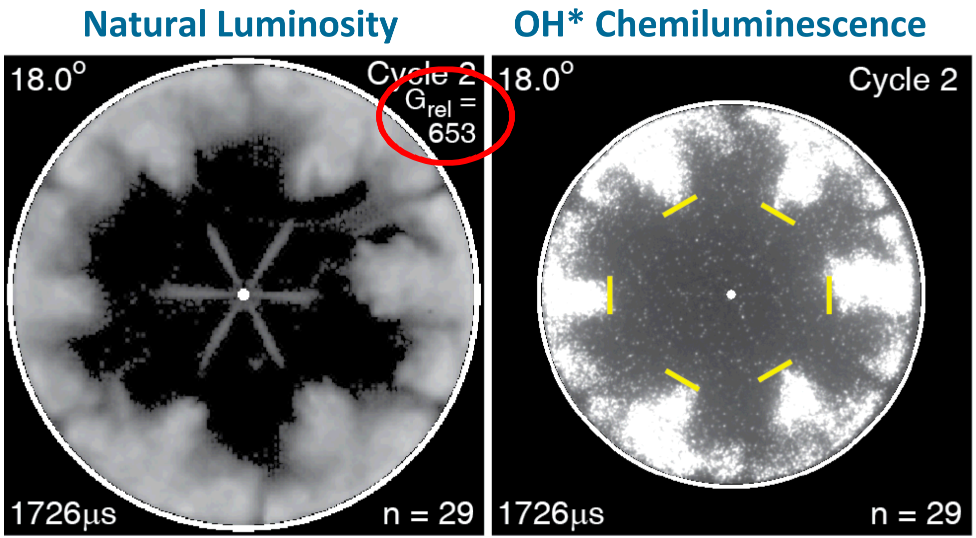
Leaner lifted-flame combustion (LLFC):
mixing-controlled CI combustion that doesn't form soot because $\phi(H) < 2$

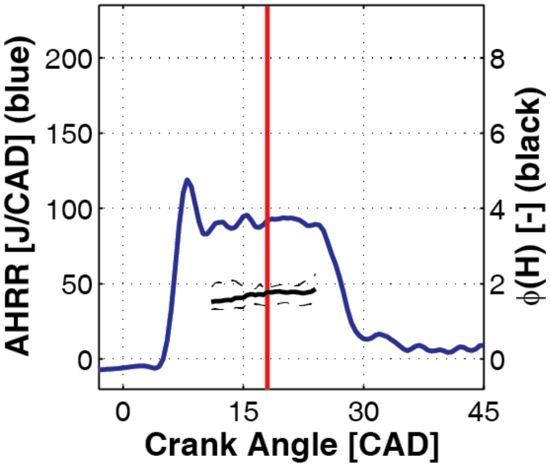


LLFC has been sustained to ~20% load with an oxygenated fuel.



TPGME = tri-propylene glycol methyl ether





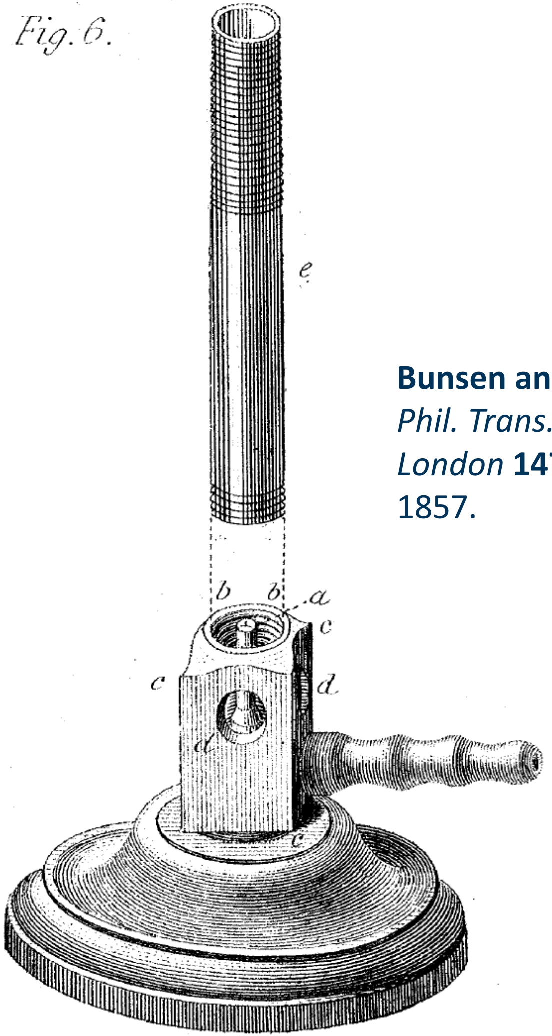
Gehmlich et al., *SAE Int. J. Engines* **9**(3):1526-1543, 2016.

#2 ULSD + 50 vol% TPGME, 1500 rpm, 6 bar $IMEP_g$, 30 °C intake manifold T, +5° ATDC start of combustion, 85 °C coolant, 21 mol% O_2 (no EGR), 240 MPa injection pressure, 110 μm injector orifices

- **Further increases in injection pressure and/or fuel oxygenation are unlikely to enable sustained LLFC at full load – a new approach is necessary**

Ducted fuel injection (DFI) can improve mixture formation in the autoignition zone.

- **Simple, mechanical approach**
  - Motivated by Bunsen burner concept

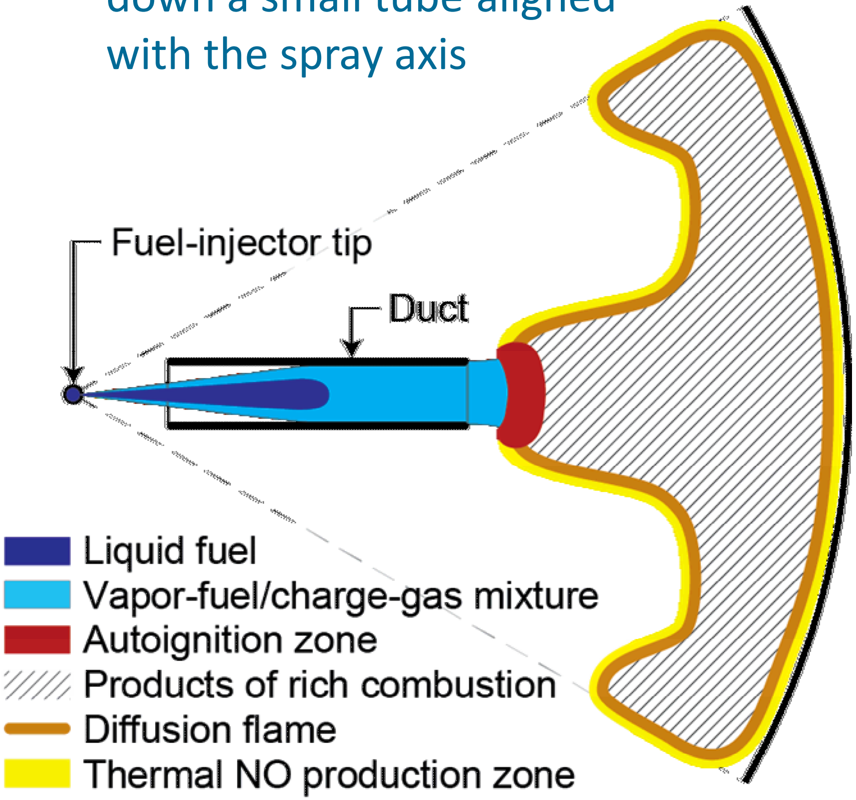


Bunsen and Roscoe, *Phil. Trans. Royal Soc. London* **147**:355-380, 1857.

Ducted fuel injection (DFI) can improve mixture formation in the autoignition zone.

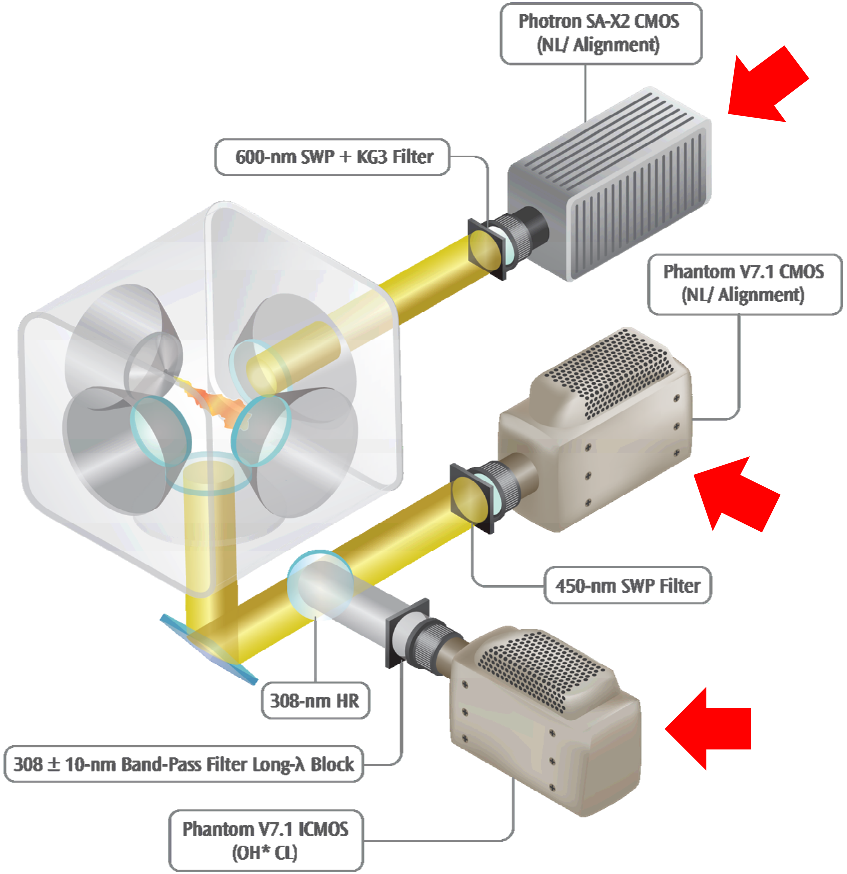
- **Simple, mechanical approach**
  - Motivated by Bunsen burner concept
  - Modifies mixture, thermal, & velocity fields
- **Effective at eliminating soot**
  - Achieves LLFC over a range of conditions
- **Tolerant to a wide variety of fuels**
  - Doesn’t require oxygenated fuel, but oxygenation is beneficial
- **Tolerant to dilution for NO_x control**
- **May improve combustion efficiency**

Basic idea: inject the fuel spray down a small tube aligned with the spray axis



1st round of DFI proof-of-concept experiments (DFI 1.0) – Diagnostics

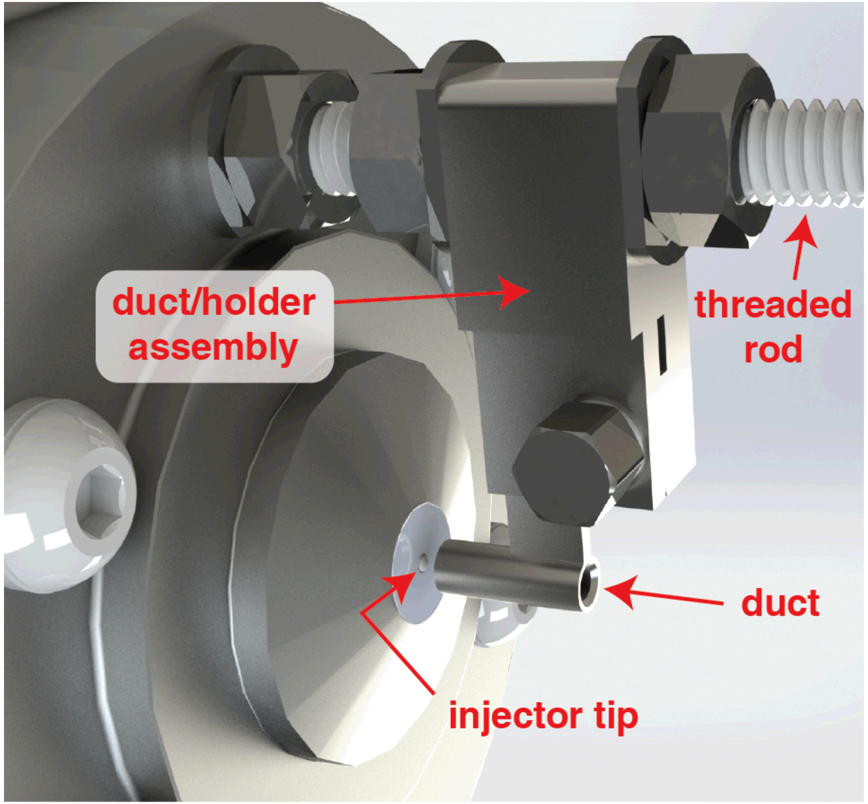
- **Testing conducted in Sandia's const volume combustion vessel (CVCV)**
- **Natural luminosity (NL)**
  - λ < 600 nm
  - Saturates if hot soot is present
- **OH* chemiluminescence (CL)**
  - λ = 308 ± 10 nm
  - Used to determine lift-off length (H
- **Alignment (bottom view)**
- **Photodiode (PD2) for SINL**
- **Pressure measurem'ts for ign. dela**



DFI 1.0 operating parameters

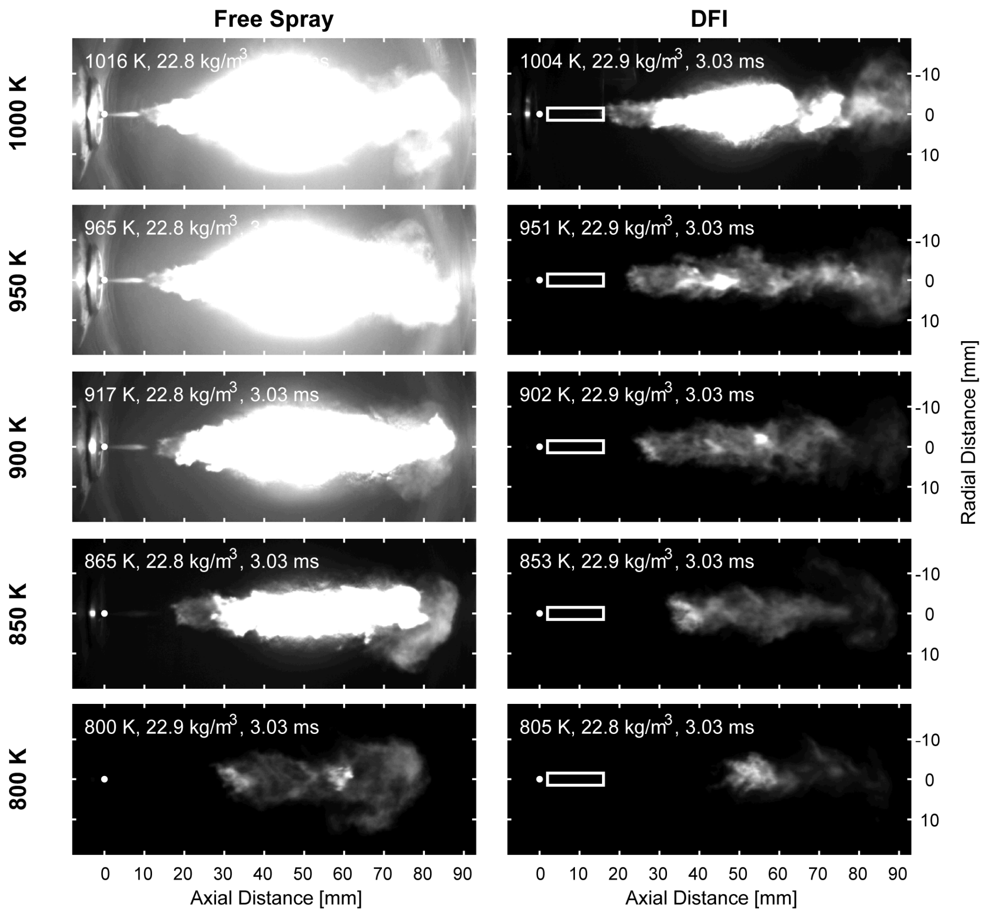
- **Ambient conditions**
  - Temperature = 800:50:1000 K
  - Density = 22.8 kg/m^3
  - Oxygen mole fraction = 21%
- **Fuel = 99+% purity n-dodecane**
- **CVCV wall temperature = 461 K (188 °C)**
- **Fuel injection**
  - Injector tip T = 363 K (90 °C)
  - Injection pressure = 150 MPa
  - Injector orifice diameter = 90 µm
  - Injection duration = 4.00 ms (actual)
  - Mass of fuel per injection = 10.7 mg

Stainless-steel duct, 1 mm wall thick., 3 mm ID × 14 mm long, positioned 2 mm downstream of injector orifice exit, 45° × 0.5 mm chamfers on inlet and outlet IDs

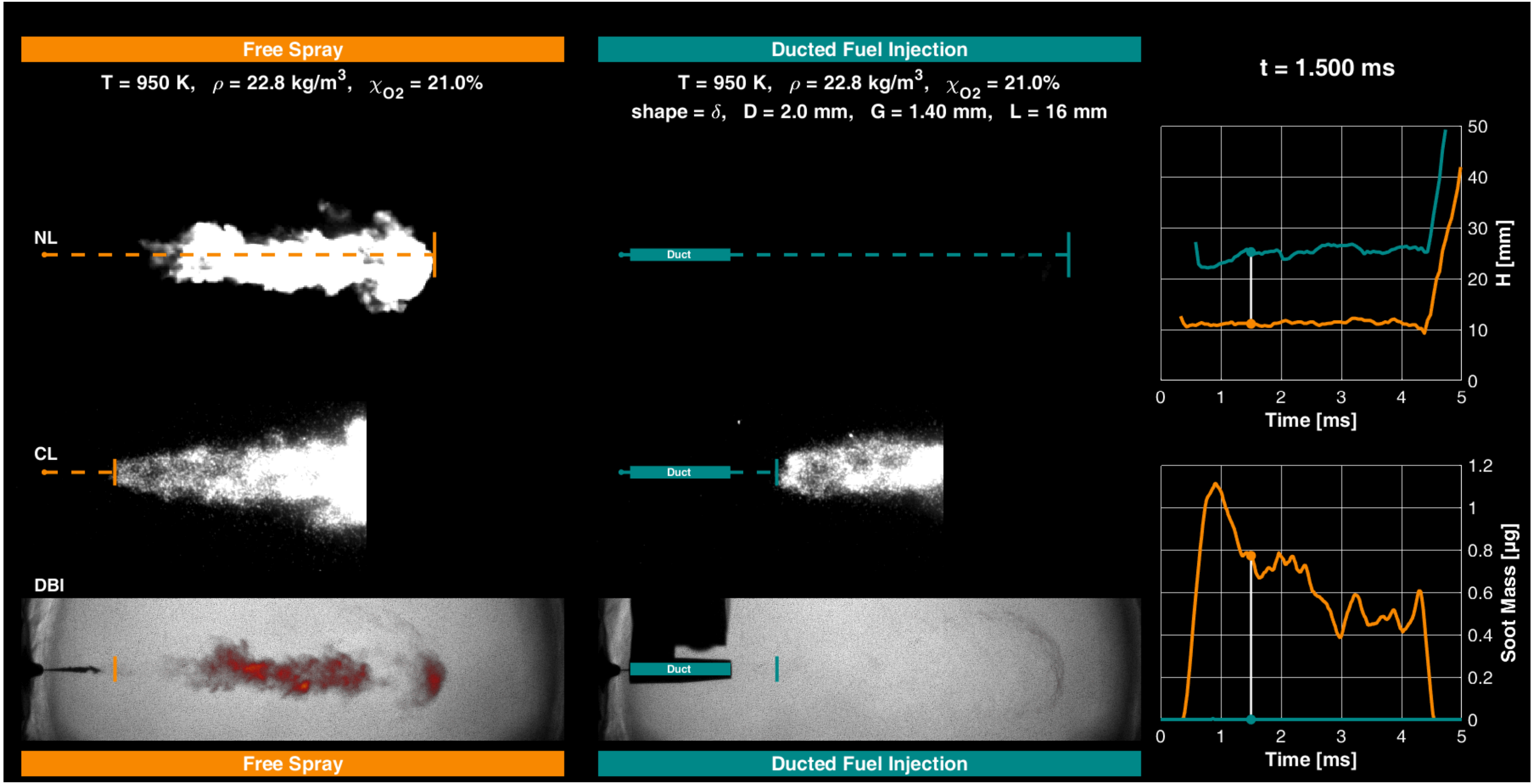


DFI 1.0 experimental results are promising.

- **Soot luminosity is reduced over a range of temperatures**
  - Even at 1000 K, where the flame is attached to the duct exit
- **NL signal for DFI drops sharply between 1000 K and 950 K**
  - Corresponds to the flame lifting from the duct exit
- **At 800 K, the free-spray and the DFI cases are both in LLFC**

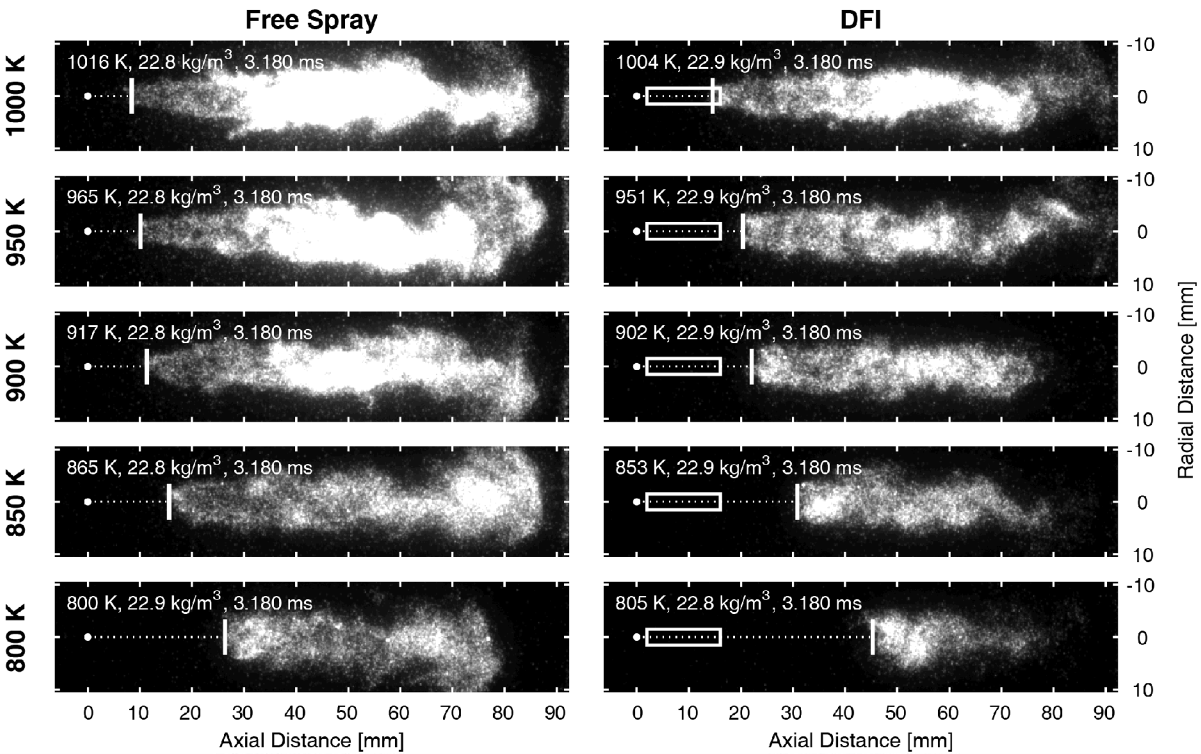


DFI 2.0 experiments confirm dramatic soot reductions.



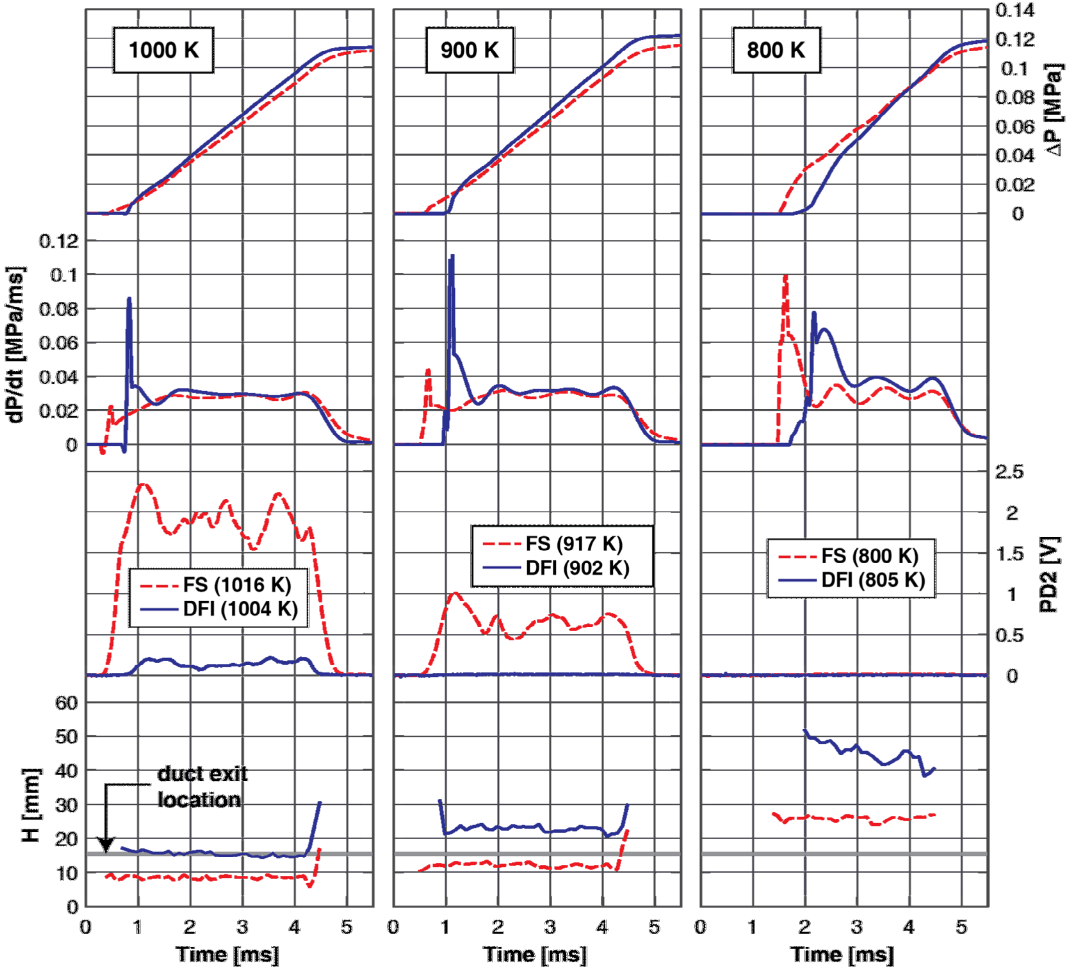
OH* chemiluminescence measurements show effects of DFI on the lift-off length and burn duration.

- **Flame is anchored at duct exit at 1000 K cond.**
  - Lifts at 950 K, where NL dropped sharply
- **Lift-off length is longer for DFI than for free-spray conditions**
- **Burnout occurs sooner for DFI conditions, consistent with a higher degree of premixing**



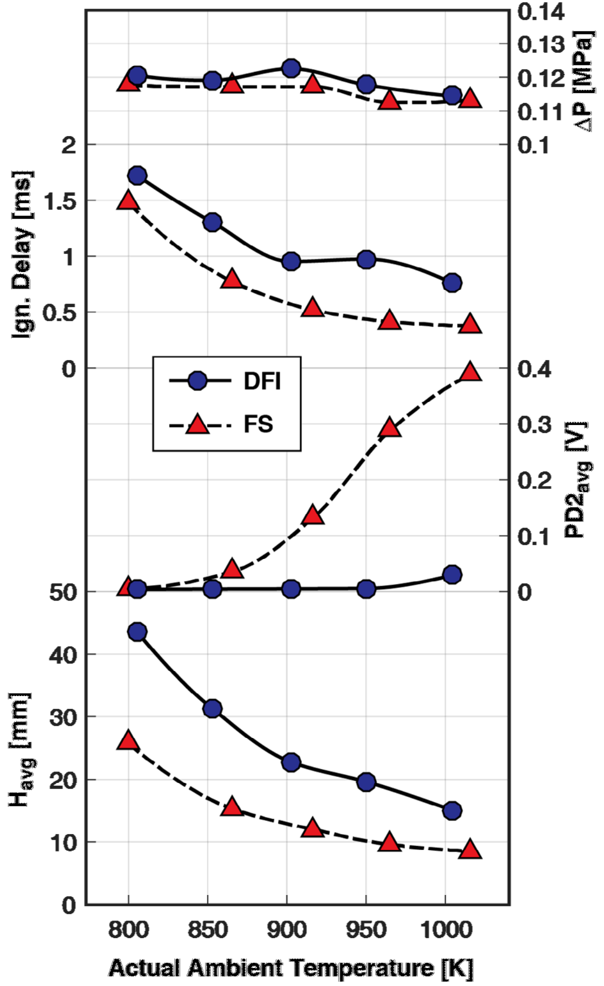
Time histories: DFI vs. free spray (FS).

- **At 1000 K, PD2 signal is ~10x lower for DFI**
  - Despite only 2-mm gap for gas entrainment into duct
- **Quasi-steady dP/dt is larger for DFI → more-premixed HR**
- **ΔP at the end of combustion is consistently slightly larger for DFI than for the free spray**



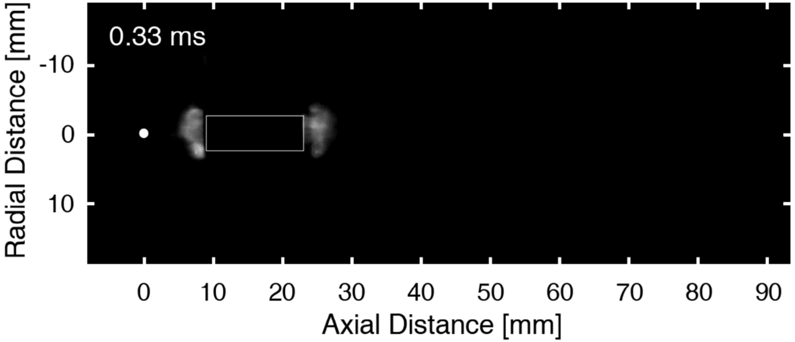
Temperature sweep: DFI vs. free spray.

- H_{avg} is consistently longer for DFI vs. the free spray
- DFI only produces appreciable PD2 signal at 1000 K
  - Comparable to free-spray PD2 signal at 850 K
  - I.e., DFI enables 150 K higher T_{amb} at constant soot
- Ignition delay is always longer for DFI
  - Curves don't follow same trend as H_{avg}
- ΔP at 5 ms after start of injection is consistently slightly larger for DFI than for the free spray
  - Combustion efficiency *might* be higher for DFI, despite lower actual ambient Ts (except at 800 K)
  - Still working to understand this…

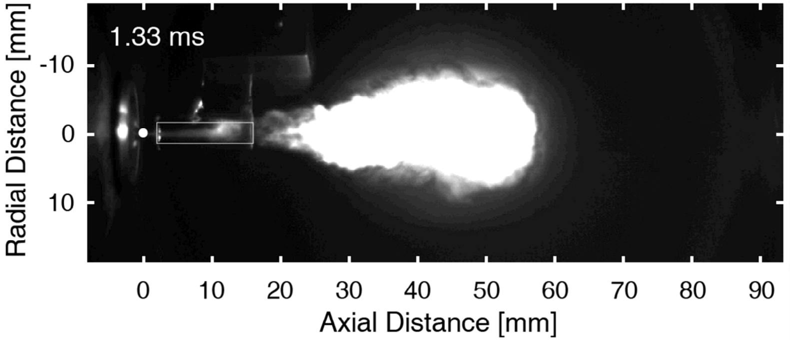


DFI has potential failure modes that should be avoided.

- Ignition within the duct can cause soot production to increase dramatically



Ignition within steel duct
D5L14G10, 1014 K, 22.7 kg/m³



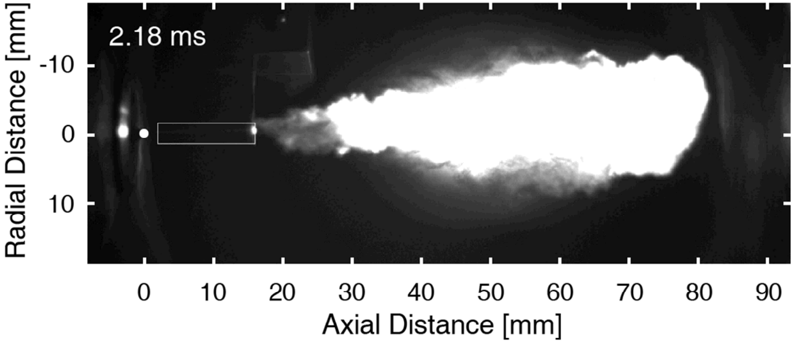
Ignition within quartz duct
D3L14G2, 911 K, 22.9 kg/m³

In this case, G was made too large!

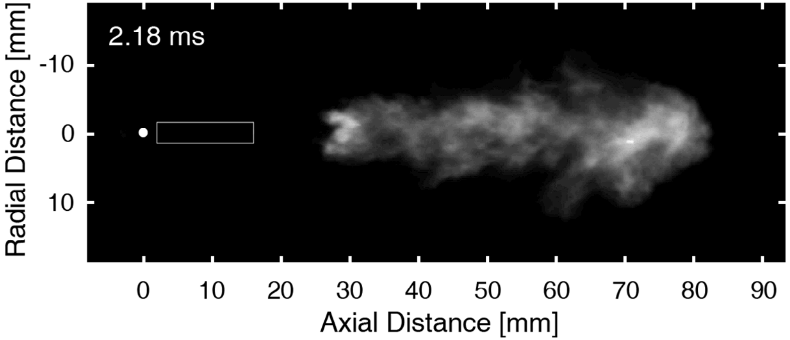
NL higher than for properly aligned steel duct, but still lower than for free spray

DFI performance is sensitive to alignment.

- Duct and spray should be as close as possible to co-axially aligned



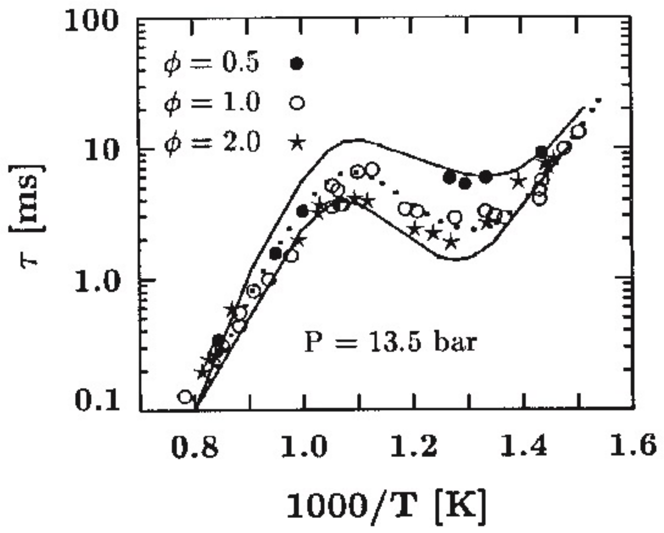
Steel duct misaligned by ~0.25 mm
D3L14G2, 905 K, 22.9 kg/m^3



Properly aligned steel duct
D3L14G2, 902 K, 22.9 kg/m^3

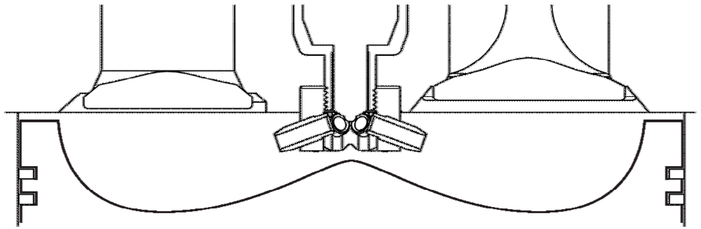
Why does DFI work? Good question!

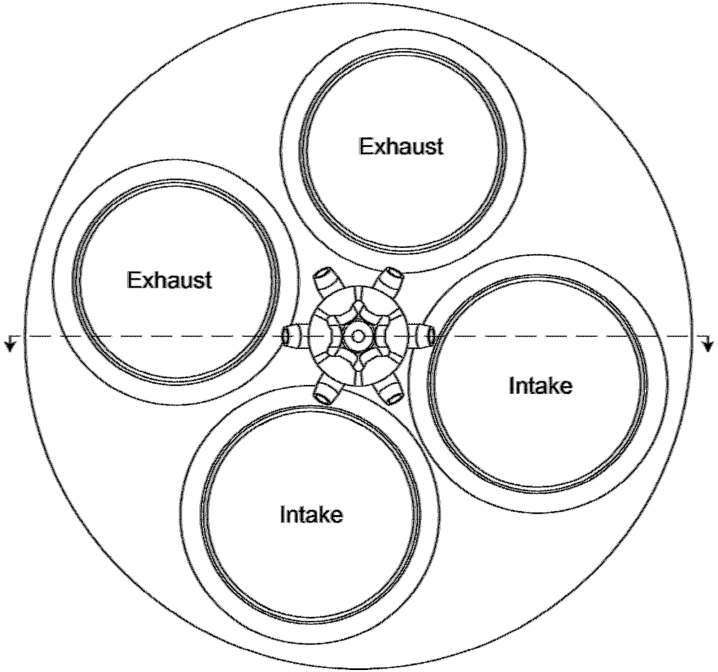
- **Mixing**
  - Transient turbulent compressible flow
  - Unknown entrainment at duct entrance and exit
- **Heat transfer**
  - Heat transfer to/from duct
  - Effect of altered entrainment on fuel vaporization
- **Alignment effects**
- **Kinetic effects**
  - Effects of mixing on ignition delay
  - Negative temperature coefficient (NTC) effects
- **Strain rate effects from the duct may also increase ignition delay**



Curran et al., *Combust. Flame* **114**:149–177, 1998

A possible engine implementation:





- **Ducts of proper length can fit within an engine (125 mm bore)**
  - D3L12 ducts aren't hit by actuating valves
  - Four longer ducts could be used if aligned between valves
- **Duct material must withstand high temperatures and thermal cycling**
  - High-temperature alloys should work fine, e.g., Inconel
- **How to ensure proper alignment?**
  - Use duct as a guide for creating injector orifices

Conclusions

- **Mixing-controlled CI combustion has great potential for further improvement.**
- **Significant synergies exist between leaner lifted-flame combustion (LLFC) and emerging renewable/oxygenated fuels.**
- **Ducted fuel injection could be a key technology for enabling LLFC in future high-efficiency engines.**
  - Simple
  - Effective at lowering soot emissions
  - Tolerant to dilution for NO_x control
  - Fuel flexible
  - May also improve combustion efficiency
- **Much remains to be learned – stay tuned!**

For more information, please see Mueller et al., *Applied Energy* **204**:206-220, 2017, doi: 10.1016/j.apenergy.2017.07.001.

Acknowledgments

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