Non-Sooting, Low Flame Temperature Mixing-Controlled DI Diesel Combustion

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Soot formation during typical diesel combustion:

\[ I / I_0 = \exp(-KL) \]

Extinction Laser

Mixing-Controlled Combustion

Pressure-rise [MPa]

Optical thickness, KL

Time after start of injection [ms]

Distance from injector [mm]
NOx formation is high during mixing-controlled diesel combustion.
Is mixing-controlled diesel combustion with low emissions possible?

- Diesel operation with mixing-controlled combustion may be needed/desired:
  - Offers more control of heat release timing.
  - Typically used during high load operation.

Objective: Investigate soot processes at low flame temperature, mixing-controlled combustion conditions:
- Low oxygen concentration (EGR) and other low flame temperature operation.
- Identify non-sooting conditions that also have low flame temperature.
Research was conducted in a unique, optically-accessible combustion vessel.

- Ambient gas conditions:
  - 800 - 1300 K.
  - 7 - 60 kg/m³.
  - O₂ conc.: 10-21% (EGR).

- Common-rail fuel injector:
  - orifice tips from 50 - 180 µm.
  - D2 (#2 diesel fuel)
  - T70 (70%-TEOP, 30%-HMN) [21.5 wt% O]

- Measurements performed:
  - soot
  - lift-off length
A “no-soot” condition is obtained when the ambient gas temperature is decreased.

**Conditions:**
- $\rho_a$: 14.8 kg/m$^3$
- $\Delta P$: 138 MPa
- $d$: 100 µm
- Fuel: D2
- $O_2\%$: 21%

**Time of PLII Laser Pulse**  
(During Mixing-Controlled Combustion)

**Graph:**
- AHRR vs. Time ASI [ms]
- SINL vs. Time ASI [ms]
- Axial distance [mm]

**Images:**
- PLII images at 1000 K, 900 K, and 850 K
- Lift-off at 850 K
The temperature at which soot does not form is much higher for a “micro-orifice”.

Conditions:
- $\rho_a$: 14.8 kg/m$^3$
- $\Delta P$: 138 MPa
- $d$: 50 µm
- Fuel: D2
- $O_2\%$: 21%

<table>
<thead>
<tr>
<th>$T_a$ [K]</th>
<th>$H$ [mm]</th>
<th>$\overline{\phi}(H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>7.4</td>
<td>4.2</td>
</tr>
<tr>
<td>1100</td>
<td>10.9</td>
<td>2.7</td>
</tr>
<tr>
<td>1000</td>
<td>18.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Mixing-controlled, non-sooting operating conditions:

\[ \Delta P = 138 \text{ MPa}, \ 21\% \ \text{O}_2 \]
Mixing-controlled, low flame temperature strategies:

- Reduced ambient oxygen concentration (simulating EGR)
  - no soot formation
  - $\phi(H) \approx 2$
  - 10% $O_2$: $T_{ad} = 1940$ K

- Reduced ambient temperature
  - Creates a lean-burn steady flame
  - $\phi(H) \approx 0.6$
  - Avoids formation of a diffusion flame
  - $T_{ad} = 2040$ K

**Conditions:**
- $\rho_a$: 14.8 kg/m$^3$
- $T_a$: 1000 K
- $\Delta P$: 138 MPa
- $d$: 50 µm
- Fuel: D2

**OH Chemiluminescence**

- 21% $O_2$
- 15% $O_2$
- 10% $O_2$

**Axial distance [mm]**

- 21% $O_2$
- 15% $O_2$
- 10% $O_2$
Using an oxygenated fuel (T70), lean-burn combustion occurs with a larger orifice:

Conditions:
- T70 fuel
- time-averaged \( \text{OH}^* \)
- \( d = 100 \ \mu\text{m} \)
- \( \rho = 14.8 \ \text{kg/m}^3 \)
- \( \Delta P = 138 \ \text{MPa} \)
- \( \text{O}_2 \% = 21\% \)

Chemiluminescence is a factor of 3 weaker for fuel-lean combustion indicating lower flame temperature.
Combustion efficiency appears acceptable for a range of lean-burn conditions.

Conditions: T70 fuel, d = 100 µm, ρ = 14.8 kg/m³, ΔP = 138 MPa, 21% O₂

![Graph showing pressure rise normalized by fuel mass injected as a function of ambient gas temperature. The graph includes two data sets for different equivalence ratios, φ(H) = 0.7 and φ(H) = 0.5.]
Low-temperature, mixing-controlled phase operating conditions:

Conditions:  D2 fuel, $\rho = 14.8 \text{ kg/m}^3$, $d = 50 \mu\text{m}$, $\Delta P = 138 \text{ MPa}$

- Soot formation avoided!
- Similar goals and behavior as low flame temperature, low soot production engine strategies.
  - Premixed HCCI
  - MK
  - Smokeless Rich
- However, heat release is closely related to mixing.
- Allows combustion during injection.
Presented results are for single jets--Could micro-orifices be used in an engine?

- In-cylinder air utilization difficulties.
- Large number of orifices are required.
  - Jet-to-jet interactions
  - Multi-injectors?
- Plugging?
- Manufacturing capabilities?
Summary and conclusions.

- IN SINGLE ISOLATED FUEL JETS, non-sooting, low flame temperature, mixing-controlled DI diesel combustion is possible.
  - Low ambient oxygen concentration (avoiding soot formation).
  - Lean-burn flames (avoiding high levels of NOx formation) using no EGR.
- Demonstrates limiting-case behavior of single jets.
- With substantial modification to engine hardware, micro-orifices and mixing-controlled diesel combustion MAY have the potential for:
  - Simultaneous engine-out PM and NOx reduction.
  - Higher load operation.
  - More control of heat release timing compared to HCCI.