Flame Lift-Off in DI Diesel Sprays: Impact on Soot Formation

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Investigate the effects of engine conditions on the evolution of soot in a diesel spray.

- How does our current understanding of diesel combustion change over a wide range of injector and in-cylinder conditions (including EGR)?

- Critical to the development of models and to the optimization of in-cylinder combustion.
Our initial research is focused on determining the flame “lift-off” length.

- Determines the amount of fuel-air premixing prior to combustion
- Emissions formation affected
  - premixing and structural changes
- Common for DI diesel sprays
  - small orifices and high injection pressure
- Database
  - model validation
  - framework for soot measurements
Research is being conducted in the Diesel Combustion Simulation Facility.

- Complete optical access
  - 108 mm cube
- Ambient gas
  - pressure: 2 - 35 MPa
  - density: 4 - 60 kg/m³
  - temperature: 600 - 1400 K
  - composition: inert, EGR, air, O₂ enriched
- Common rail injector
Experimental setup.

+ Natural light emission at 310 nm:
  - OH chemiluminescence a significant component

+ Fuels:
  - DF2
  - low-sooting
  - heptane
Lift-off length definition.

- Lift-off length = 22.0 mm
- Camera gate = 30 µs
- Soot Lift-off Length based on time-averaged light emission at 310 nm.
- Lift-off length defined as the farthest upstream location with a light intensity greater than 8% of full scale (0-255).
Time-averaged line-of-sight images of 310 nm light emission (3 ms camera gate).

DF2, \( d=246 \, \mu m \), \( \Delta P_{\text{inj}}=140 \, \text{MPa} \), Density=14.8 kg/m\(^3\)
Effects of in-cylinder conditions and orifice diameter on lift-off length.
Lift-off length depends linearly on injection velocity.

- Fuel: DF2
- Gas density: 14.8 kg/m$^3$
- Gas temp: 1000 K
The quantity of fuel and air premixed prior to combustion is affected by lift-off.

DF2, Temperature = 1000 K, Density=14.8 kg/m³

\[ \zeta_{\text{st}}(\%) = \frac{10}{3} \left( \sqrt{1 + 16 \left( \frac{x}{s^+} \right)^2} - 1 \right) \]

\[ s^+ = \frac{d}{\tan \alpha} \cdot \sqrt{\frac{\rho_f}{\rho_{\infty}}} \]

Lift-off \[\text{Lift-off \ [mm] or } \zeta_{\text{st}} \ [\%]\text{]}

Injection velocity \[\text{Injection velocity \ [m/s]}\]
The relationship between fuel vaporization and combustion is affected by $\Delta P_{inj}$ and $d$.

- DF2, Temperature=1000 K, Density=14.8 kg/m$^3$
Diesel combustion is evolving in response to changes in $T$, $\rho$, $\Delta P_{inj}$, $d$, etc. 

Liquid fuel droplets
Vapor fuel/air mixture
“Premixed” combustion
Diffusion flame
Soot formation/growth
Combustion products

- Lift-off length
- Liquid length

$\zeta_{st} = 9\%$
$\zeta_{st} = 15\%$
$\zeta_{st} = 20\%$

$35\text{ MPa}$
$250\text{ µm}$

$140\text{ MPa}$
$250\text{ µm}$

$140\text{ MPa}$
$180\text{ µm}$

$m_f \longrightarrow 4 \times \Delta P \longrightarrow 2 \cdot m_f \longrightarrow d/\sqrt{2} \longrightarrow m_f$
Soot incandescence as a function of lift-off length.

Decreasing ambient temperature

Soot incandescence (a.u.)

Lift-off length [mm]
Soot incandescence approaches zero as $\phi$ approaches two at the lift-off length.

\[ \phi = \frac{30}{\sqrt{1 + 16 \cdot \left( \frac{X}{s^+} \right)^2}} - 1 \]

\[ s^+ = \frac{d}{\tan \alpha} \cdot \sqrt{\frac{\rho_f}{\rho_\infty}} \]
Comparison of predicted soot precursor and soot incandescence trends.

(Flynn, et al., SAE 1999-01-0509)
Summary (initial results).

- Engine load conditions (gas temperature and density) and injection parameters (orifice diameter and injection pressure) strongly affect lift-off: — resulting in structural changes in diesel combustion.

- Historically, changes made to meet emissions regulations have contributed to a systematic evolution of diesel combustion processes.

- How do these changes affect soot formation?

- What about parameter ranges not considered yet?