Progress towards understanding combustion inefficiencies:

In-cylinder sources of CO and UHC

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Factors affecting brake fuel efficiency

\[ \eta_b = \eta_m \eta_t \eta_c \]

- Pumping work
- Friction
  - Downspeeding
  - Downsizing
  - Materials
  - Lubricants
  - Additives
- Accessories
Factors affecting brake fuel efficiency

\[ \eta_b = \eta_m \eta_t \eta_c \]

\[ \int p \, dV \]

Net chemical energy released

Influenced by:
- Compression ratio (Expansion ratio)
- Specific heat ratio
- Combustion phasing and rate of heat release
- Heat transfer losses
Factors affecting brake fuel efficiency

\[ \eta_b = \eta_m \eta_t \eta_c \]

Net chemical energy released

\[ m_f Q_{LHV} \]

- Low \( \eta_c \) manifested by “fuel” in the exhaust gases (CO, UHC, H\(_2\) ...)
- Normally high
  - > 0.98 diesels
  - > 0.95 spark
- Can drop drastically for low-temperature diesel or HCCI
Overview

- Description of UHC and CO sources from **early-injection (PCI-like)** low temperature combustion systems
  - Understanding developed from homogeneous reactor simulations
  - Experimental images of in-cylinder UHC and CO

- Description of UHC and CO sources from **late-injection (MK-like)** low temperature combustion systems
  - Understanding developed from homogeneous reactor simulations
  - Experimental images of in-cylinder UHC and CO

- Contrast to emissions sources from conventional (**Euro 5**) calibrations

- Implications for combustion chamber design and operating condition selection
Emissions behavior of early-injection, PCI-like combustion

- Within a range of intake charge O\textsubscript{2} concentrations, early injection low-temperature combustion schemes can provide low soot, low NO\textsubscripts{X}, and acceptable noise.

- At high dilution levels, CO and UHC emissions rise and combustion efficiency deteriorates.

- We will examine UHC and CO sources for a 10% oxygen concentration in the intake charge, which provides a combustion efficiency of \( \approx 98\% \).
Homogeneous reactor simulations, following realistic pressure and temperature histories, help us understand the impact of equivalence ratio on CO and UHC emissions.
Other than ignition timing and temperature related differences in peak rate, the heat release rate characteristics of rich mixtures are similar to those of clean-burning mixtures.

Rich mixture emissions are mixing-limited.
Impact of equivalence ratio on early-injection, PCI-like combustion

For lean mixtures, the heat release is retarded and slowed compared with clean-burning mixtures.

Lean mixture emissions are kinetically-limited

CO oxidation is impeded first, then UHC for very lean mixtures.
For PCI-like combustion, the CO and UHC are not co-located within the clearance volume.

Data at 30°CA

- CO is broadly distributed throughout the squish volume, with greater concentrations near the piston.
- Unburned fuel is observed near the injector, and to a lesser extent near the bore wall.
- Partially-burned fuel is generally found between fuel and CO—showing the direction of reaction progress.
- Simulations (and exp. parameter sweeps) show that squish volume mixture is over-all fuel-lean.
By 50°CA, it is clear that the near-injector and squish regions dominate CO and UHC emissions.

Data at 50°CA

- Measured CO and UHC
  - At 50° CA, 83% of the cylinder volume is within the clearance volume.
  - Distributions of CO and UHC components are similar to those seen at 30°CA—just stretched axially.
  - The flow exiting the bowl is clean.

Modeled UHC (CO is similar)

Mean flow structures and squish volume emissions are well predicted, even if CO and UHC emissions are not.
Single-cycle images reveal UHC within the bowl and better characterize squish volume UHC

UHC within the bowl:
- Observed infrequently
- More frequent with retarded SOI
- Absent with advanced SOI
- More pronounced at higher load

Simulations capture the general fuel distribution, but mixing is underpredicted

Within the squish volume, UHC fluorescence is observed from:
- Diffuse (fuel lean) bulk gas UHC
- Apparent liquid films on the piston top
- Crevice flows
The near-injector UHC is made up of both liquid and gaseous fuel.

Intense, spherical regions show liquid fuel near the injector... ...that are also seen in elastic scatter images.

Diffuse fluorescence also seen near the cylinder center is characteristic of gaseous UHC.

End-of-injection over-leaning is one possible source of this diffuse fluorescence.

Musculus, et al. SAE 2007-01-0907
Emissions seen in both the squish volume and near-injector regions drop significantly with load.

- Both near-injector and squish volume emissions decrease significantly with load.
- Central cylinder CO at higher loads is consistent with better oxidation of near-injector UHC.
- Optical data correlate closely with engine-out emissions.

![Graphs and images showing emission changes with load](image-url)
Higher resolution, cycle-averaged images show impact of load on squish volume UHC sources

As load increases:

1) bulk gas UHC from the near-injector and central cylinder region decreases
2) the diffuse, bulk gas signal within the squish volume decreases
3) the UHC associated with crevice flows and piston top films increases

The 1st and 2nd factors dominate

Note also the predicted fuel-lean UHC in the bowl periphery is clearly observed, and vanishes at the highest load
Squish volume emissions are minimized by small squish heights and low spray targeting.

Statistically significant set of experiments, incorporating repeated engine builds at each condition.

Conventional diesel design guidelines still apply when PCI-like combustion is employed in typical diesel hardware geometries:

A large k-factor and spray targeting within the bowl is desirable.
Emissions behavior of late-injection, MK-like combustion

- Like early injection schemes, late-injection LTC can provide low soot, low NO$_x$, and acceptable noise.

- At retarded timings, CO and UHC emissions rise and combustion efficiency deteriorates, just as noise levels become acceptable.

- We will examine UHC and CO sources for a late injection case which provides a combustion efficiency of ≈ 97%.
Impact of equivalence ratio on late-injection, MK-like combustion

For rich mixtures, the emissions characteristics do not change as injection is retarded.
Impact of equivalence ratio on late-injection, MK-like combustion - lean mixtures

For lean mixtures, higher equivalence ratios are required to complete oxidation at retarded timing.

Oxidation is limited by the failure to transition into strong high temperature combustion – leading to similar limiting equivalence ratios for CO & UHC.
With late injection, there is evidence of CO, PAH, and C$_2$ exiting the bowl at 30°CA (as predicted).

SOI$_c$ = -2.3° (Data at 30°CA)

**Measured CO and UHC**

- The (fuel-lean) squish volume is again a dominant source of UHC and CO, despite spray targeting deep within the bowl.
- Fuel is again observed near the injector, with small amounts of CO.
- Experiments appear to support model predictions of fuel-rich UHC leaving the bowl.

**Modeled UHC**

*CO is similar*
By 50 °CA, however, the rich-mixture source from the bowl has vanished.

At this crank angle, the flow exiting the bowl, as was seen with early injection timing, is very clean.

Measured CO and UHC

SOI\textsubscript{c} = -2.3° (Data at 50°CA)

Modeled UHC (CO is similar)
With more retarded SOI, the squish volume UHC and CO emissions completely dominate.

- Notable increases in squish volume concentrations are observed for both UHC and CO.
- Larger increase in engine-out UHC than CO is consistent with homogeneous reactor simulations of lean mixtures.
How do conventional (Euro 5) combustion UHC and CO distributions compare?

The Euro 5 calibration features a main injection timing very similar to our late-injection, low temperature condition.

Euro 5 emissions are low CO and UHC, but relatively high soot and NOx.
With conventional combustion, UHC and CO are predominantly found in the near-injector region.

- Very intense “UHC” signals may have a soot component.
- CO observed in the squish volume at 30°CA appears to fully oxidize by 50°CA.
Summary & implications for operating condition selection and combustion chamber design

- Fuel dribble from the nozzle sac volume is a significant (though not a dominant) source of UHC and CO emissions (≈ 15-30% ?)
- Significant gaseous UHC in fuel-lean mixture is seen in the near-injector region. Under some operating conditions, this may dominate engine-out UHC
- Fuel-lean mixture within the squish volume is the dominant source of CO emissions from both early- and late-injection LTC strategies at low loads. It is also a significant, and likely dominant, source of UHC

Strategies to reduce squish volume CO and UHC include:

- Minimize squish height, target spray well within the bowl
  (generally prevent lean mixture formation within the squish volume)
- Attack combustion noise by means other than increased dilution or SOI retard
  Reduce ignition delay through pilot injections? (lean mixture is the problem)
  Disrupt/split heat release with an appropriately timed post injection?
- Increased T_{in} (high pressure EGR? VVA?)
- Adopt a more open chamber, lower swirl design?
  Better BSFC; with part-load LTC, no part-load soot catastrophe!