High-Efficiency Clean Combustion Design for Compression Ignition Engines

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Overview

### U.S. Heavy Duty Emission Standards

- **NO\textsubscript{X} (g/hp-hr)**
  - 2004
  - 1998

- **PM (g/hp-hr)**
  - 2010
  - 2007

### U.S. Light Duty Emission Standards

- **NO\textsubscript{X} (g/mi)**
- **PM (g/mi)**

- Tier 2, Bin 10 (2007-2010)
- Euro 3 (2000)
- Euro 4 (2005)
- Euro 5 Prop

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The $\phi$ vs. T diagram is commonly used in diesel combustion discussions.

Combustion processes pass through a particular path in this space.

Time is not represented in the figure.
Equivalence Ratio ($\phi$) vs T Space – Navigating the Terrain

Fuel – charge mixing line (green): As the fuel and charge mix, the temperature and equivalence ratio of the mixture will follow this line. The location of the line changes with $T_{\text{charge}}$.

- VVA
- $T_{\text{intake}}$

**Ignition zone**

**CO / UHC oxidation limit**

**Soot production zone**

**NOX production zone**

**Temperature (K)**

500 1000 1500 2000 2500 3000

**Equivalence Ratio ($\phi$)**

0 1 2 3 4 5 6

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Ignition zone (grey): This is the temperature range above which a diesel fuel / air mixture will ignite rapidly.
Equivalence Ratio ($\phi$) vs T Space – Navigating the Terrain

Flame temperature lines (red): The adiabatic flame temperature of a fuel / charge mixture at the given equivalence ratio.
Soot production zone (blue): This denotes the region where soot is formed in significant quantities.
Equivalence Ratio ($\phi$) vs T Space – Navigating the Terrain

NOx production zone (cyan): This denotes the region where NOX is formed in significant quantities.

- NOx production zone (cyan):
- CO / UHC oxidation limit:
- soot production zone:
- T_{charge}
- T_{flame}
- 21% O$_2$
- 15%
- 10%
- 8%

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Equivalence Ratio ($\phi$) vs T Space – Navigating the Terrain

CO / UHC oxidation limit (orange): Must complete combustion above this temperature in order to consume CO and unburned HC.
Conventional Diesel Combustion

Fuel mixes with charge (A) until the ignition temperature is reached.

The path shows the trajectory of a **fuel parcel** undergoing a conventional diesel combustion event.
The fuel first undergoes a rich premixed reaction (B-C) in which part of the fuel energy is released.
The remainder of the fuel energy is released as the rich products continue to mix with oxygen (C-D) in a diffusion flame.
Conventional Diesel Combustion

The combustion products continue to mix throughout the chamber (D-E).

Equivalence Ratio ($\phi$)

Temperature (K)

fuel – charge mixing line

premixed

soot production zone

diffusion

CO / UHC oxidation limit

ignition zone

T$_{\text{charge}}$

T$_{\text{flame}}$

NO$_x$ production zone

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New Combustion Modes (PCCI) – Reducing NOx and Soot

Increased mixing (lower $\phi$ at ignition) comes from longer ignition delay via reduction in $T_{\text{charge}}$ at injection.

Flame temperature reduction comes from reduced oxygen concentration via EGR.

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Flame temperature reduction comes from reduced oxygen concentration via EGR.
Soot Reduction Through Low O₂ Concentration

In this scenario, soot is never formed due to the low temperature during ignition and combustion.

Difficult to avoid combustion products (CO / UHC).
The ideal process will create the necessary conditions in which most of the energy release will take place in the region shown.
New Combustion Modes (PCCI) – Reducing NOx and Soot

Equivalence Ratio ($\phi$)

500 1000 1500 2000 2500 3000

21% O2
15%
10%
8%

NOx production zone

Soot production zone

Improvements in the hardware available have improved our ability to use PCCI modes and increased their applicable range of speed and load.

Equivalence Ratio ($\phi$)
End of Presentation

- BackUp Material
Early vs. Late PCCI

- PCCI mode requires a longer ignition delay.
- How to lengthen the ignition delay:
  - Lower T at SOI
  - Lower [O2] at SOI
- In order to access lower temperature, the injection must move away from TDC:
  - Advance timing for early PCCI
  - Retard timing for late PCCI
- Compression ratio and charge temperature will also affect the injection range.
Some Practical Limitations

- Impossible to achieve temperatures higher than the flame temperature – operation in the high T – high $\phi$ region is precluded.
- The ignition process must pass through the region shown (need better words here!)
- End of combustion temperature must remain high enough to insure complete oxidation of CO and UHC compounds.