Diesel Engine Technology

14th U.S./North American Mine Ventilation Symposium

Diesel Workshop

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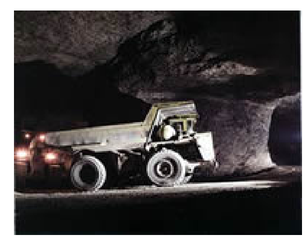
Overview

- Describe in-cylinder emissions formation process

- Describe technical function of in-cylinder diesel emission controls
    - Charge air compression
    - Charge air cooling
    - Exhaust gas recirculation
    - Mixing and charge motion
    - Fuel delivery and injection strategies
    - Various other technologies
        - Importance of computer controls
    - Future directions


Formation of Emissions

Regulated Emissions

Ideal combustion

- Fuel(C_xH_x) + air(O_2,N_2) → carbon dioxide(CO_2) + water(H_2O) + nitrogen(N_2)

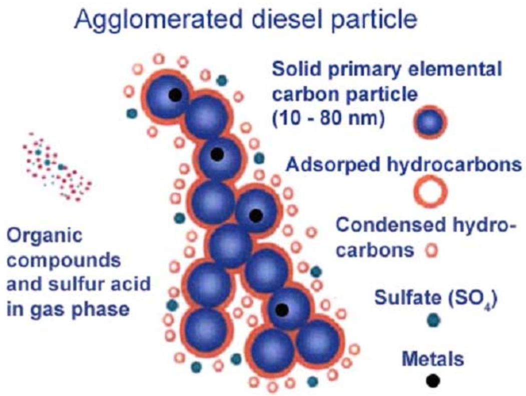
Unwanted Emissions

- PM (Particulate Matter)
  - EC (Elemental Carbon)
  - Organic Compounds (OC/SOF)
  - Ash
  - Sulfur Dioxide(SO_2)
- NO_x (Nitrogen Oxides)
  - NO and NO_2
- HC (Hydrocarbons)
- CO (Carbon Monoxide)

Particulate Matter - EC

- **Elemental Carbon (EC)**
  - *inorganic carbon*, “soot”, “black carbon”, black smoke
  - Pyrolysis of fuel within the fuel injection plume
    - insufficient oxygen to convert carbon in fuel (C_xH_x) into CO_2
    - solid carbon particles(C)
    - most oxidize later during combustion, but some are emitted

  - Control by increasing surface area contact of fuel and air



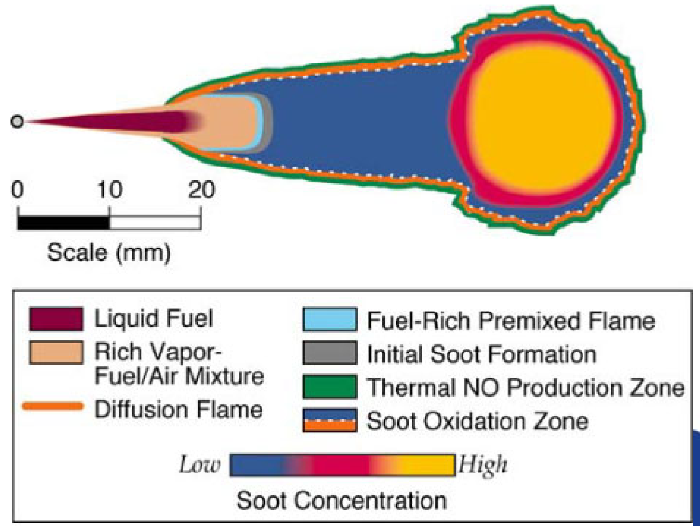
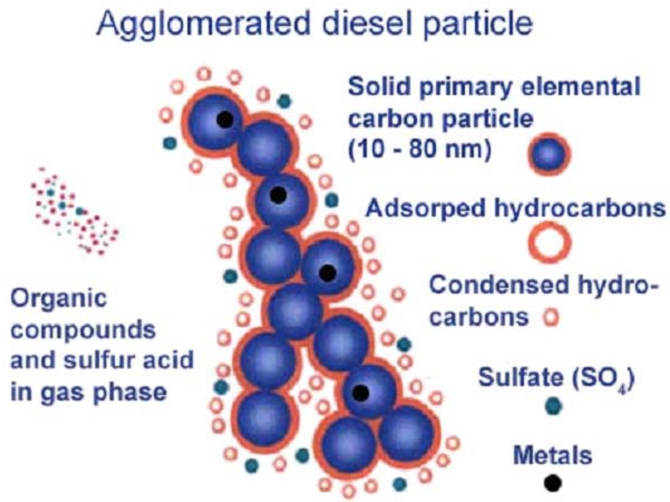


Figure 1. Quasi-steady Diesel combustion plume as presented by DEC (1997). Courtesy Dr. John E. Dec (Sandia National Laboratories).

Particulate Matter - OC

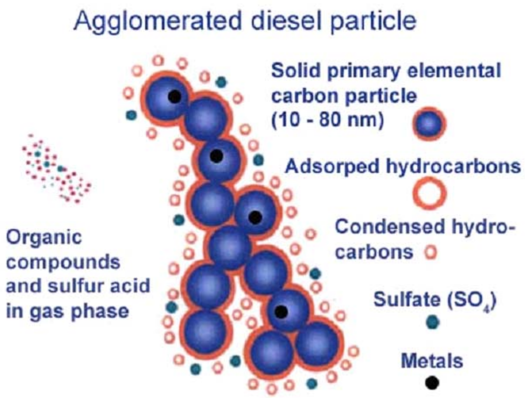
- **Organic Carbon (OC)**
  - HC in fuel and lubricating oil not fully oxidized during combustion
  - Forms organic material in particle phase
    - Small in size
    - Can/will condense and adsorb onto larger EC particles

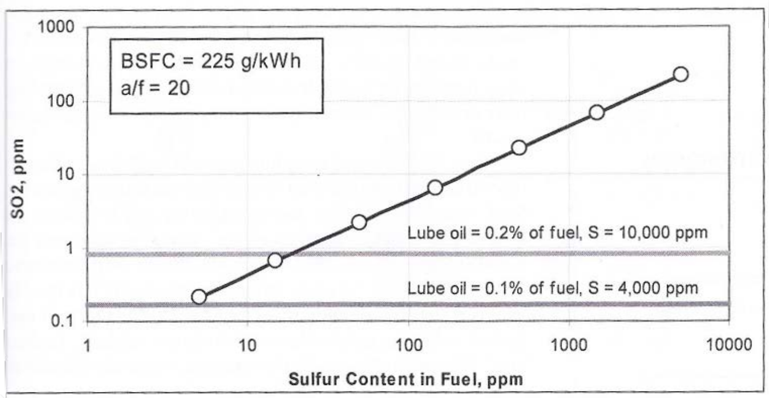
  - Control by reducing oil consumption, improving injector design and timing, improving fuel and oil formulations



Particulate Matter – Ash, SO_2

- **Ash**
  - Metallic PM formed from metal additives present in lubricating oil and engine wear.
  - Mechanically problematic – will not burn in secondary reactions, can accumulate within exhaust system
  - Control by reducing oil consumption and improving fuel and oil formulations (CJ-4 oil)
- **Sulfur Dioxide (SO_2)**
  - Sulfur present in fuel and lube oil can oxidize during combustion
  - Deactivates catalysts in exhaust
  - Control by reducing sulfur content of fuel and oil (Ultra-low sulfur fuel)





Gaseous Emissions - NO_x

- **Nitrogen Oxides (NO_x)**
  - $NO_x = NO + NO_2$
  - Molecular nitrogen bonds w/ oxygen at <u>high temperatures</u>
  - NO_x forms in region outside of fuel/flame plume where fuel to air ratio is optimal for efficient, high temperature combustion

  - Control is "simple", lower peak flame temperatures = lower NO_x

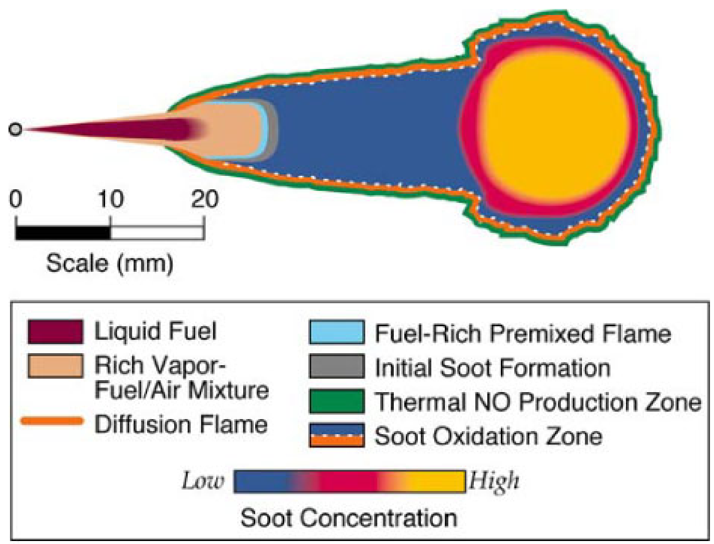
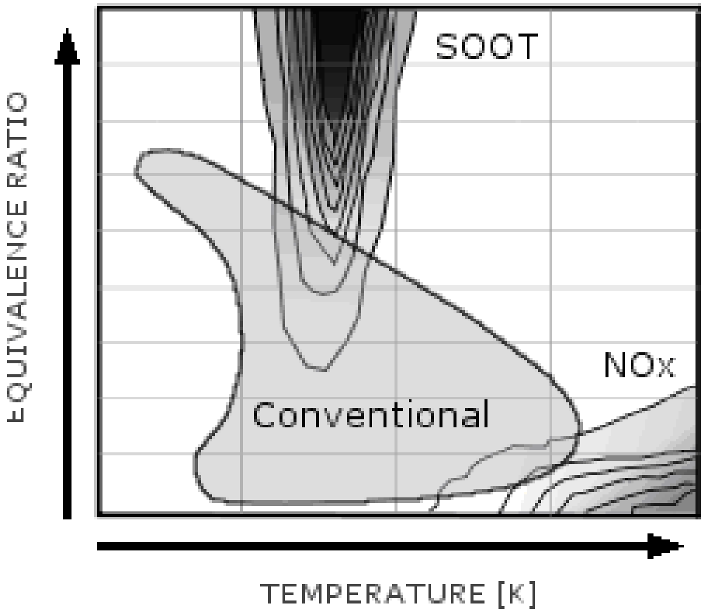


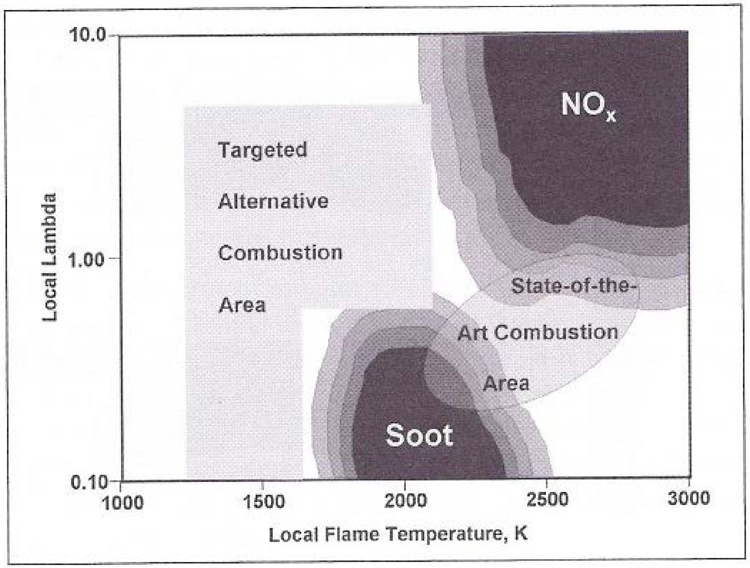
Figure 1. Quasi-steady Diesel combustion plume as presented by DEC (1997). Courtesy Dr. John E. Dec (Sandia National Laboratories).

Gaseous Emissions - HC

- **Gas Phase Hydrocarbons (HC)**
  - Fuel or lube oil escapes the chamber without oxidizing during the combustion process
  - Can adsorb onto EC particles or nucleate and contribute to PM emissions
  - Main sources
    - residual fuel within the injection nozzles after injection
    - fuel that has been overly mixed beyond lean limit conditions during ignition delay
    - Oil consumed during combustion
  - Control by reducing oil consumption, improving injector design and timing, improving fuel and oil formulations

NO_x / PM tradeoff





* equivalence ratio is a measurement of the localized fuel to air

The issue

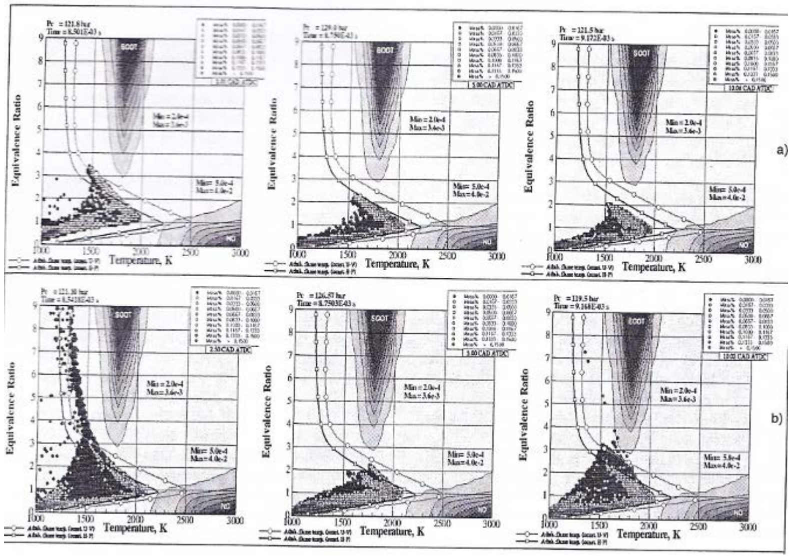
Increase air/fuel ratio → lean, efficient combustion → higher flame temps → form NO_x
Decrease air/fuel ratio → rich, deficient combustion → fuel pyrolization → form PM

NO_x / PM tradeoff

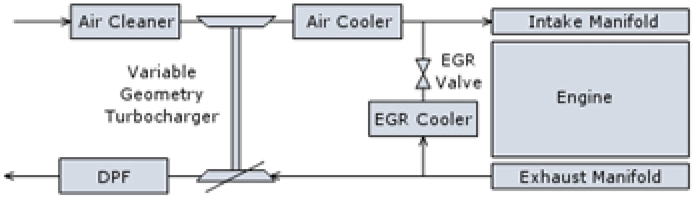
- **High in-cylinder temperatures** - optimize performance, use aftertreatment to clean up NO_x

- **Lower in-cylinder temperatures** - make up for efficiency losses elsewhere, use exhaust particulate filter and DOC to clean up PM/HC/CO

- **Ultra-low in-cylinder temperatures** – avoid NO_x and PM formation altogether



Technologies



Charge air compression

Turbochargers (exhaust driven) and superchargers (shaft driven)

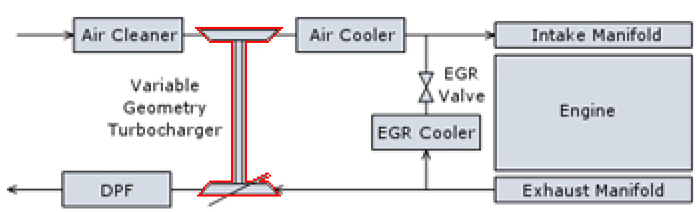
- Increase pressure of intake air
  - Force more air mass into chamber during intake
    - Make more oxygen available to fuel during combustion
    - Enhance fuel/air mixing during intake
- Overall, reduce rich regions of flame → lower PM formation

Variable Geometry Turbochargers (VGTs)

- Vanes open and close to vary compression in response to engine speed
- Provide boost even at low speeds
- Regulate manifold pressure differential to promote exhaust gas recirculation (EGR) flow

Electrically Assisted Turbocharger

- Electrical motor driven at low speeds
- Regenerate electrical power w/ excess exhaust energy at high speeds

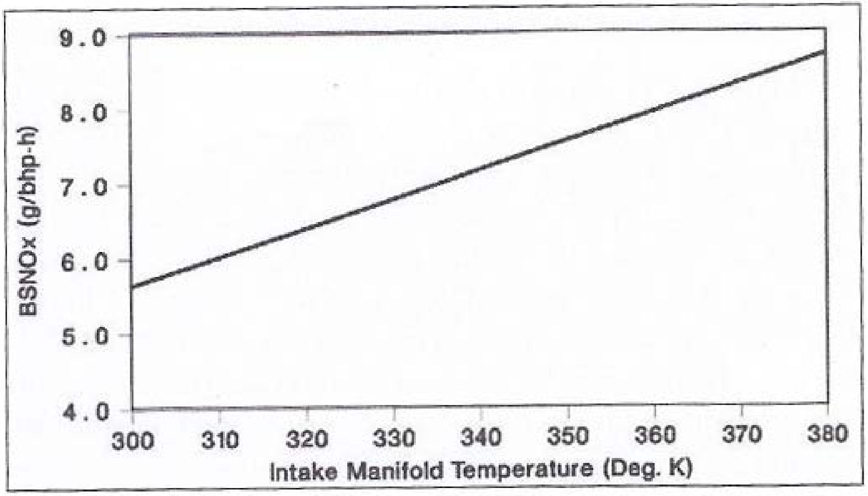


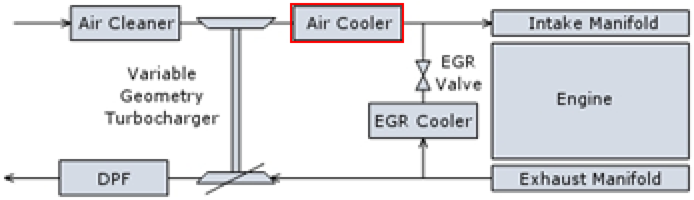
Charge air cooling

Aftercooler

- Isobaric cooling of intake air
- Combats heating effects of intake air compressor

- Reduced intake air temperature = lower combustion temperatures
  - Reduce NO_x formation





Exhaust Gas Recirculation

Reduce in-cylinder temperatures by routing a portion of exhaust flow back to intake

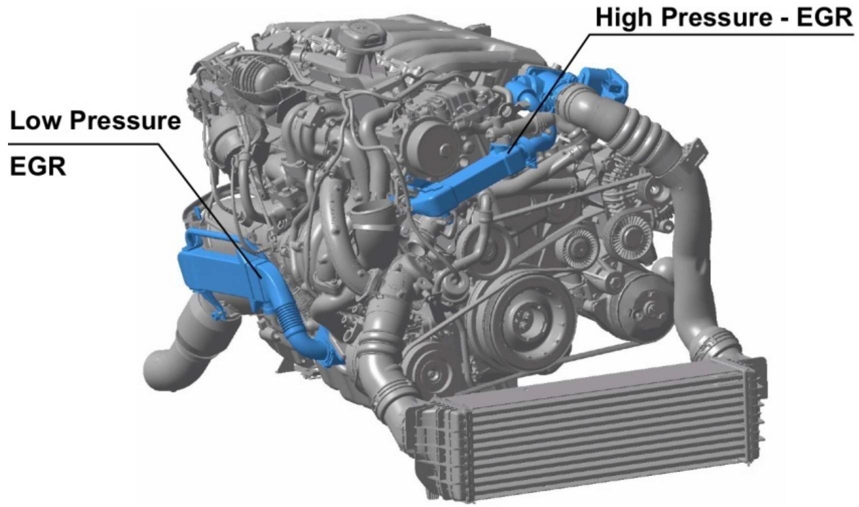
Significantly lower NO_x formation at the expense of possible increases in HC, CO and PM as well as thermal efficiency losses due to increased pumping work.

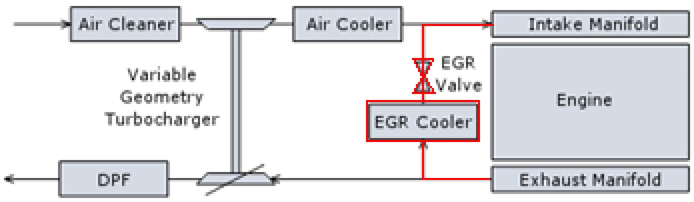
Mechanisms of operation

Thermal effect – CO_2 and H_2O increase specific heat capacity of charge air

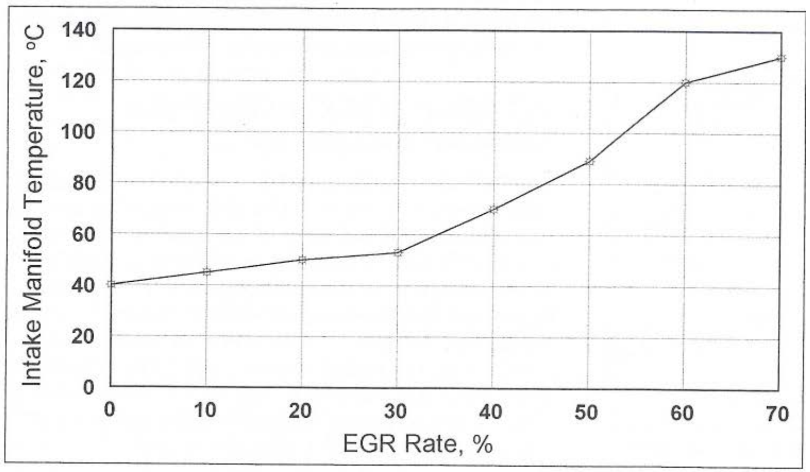
Dilution effect – Replace certain amount of O_2 with incombustible CO_2 and H_2O

Chemical dissociation effect - dissociation of CO_2 and water vapor at high temperatures is an endothermic process

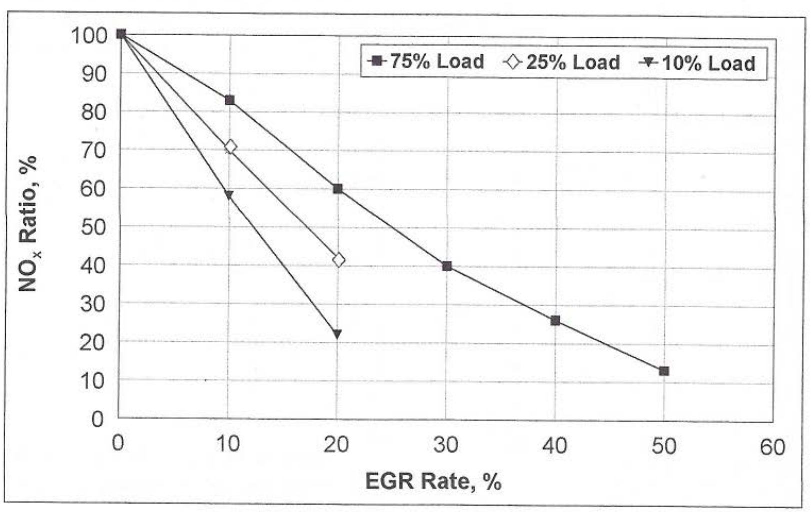


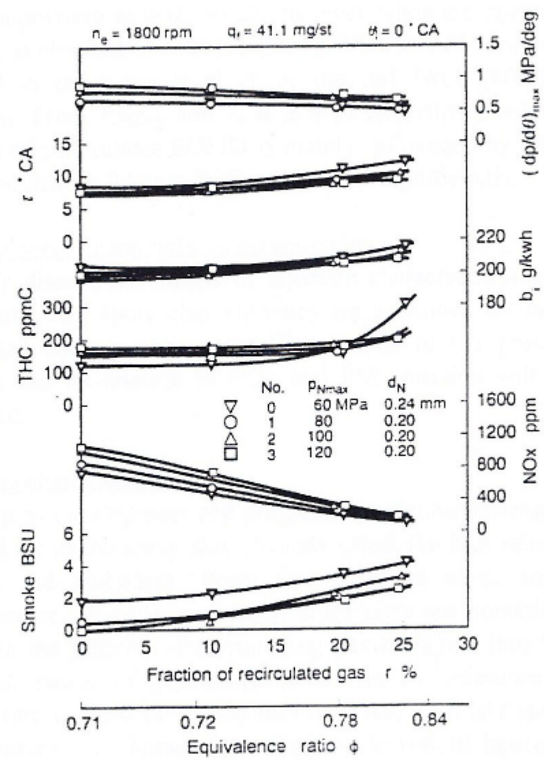


Exhaust Gas Recirculation

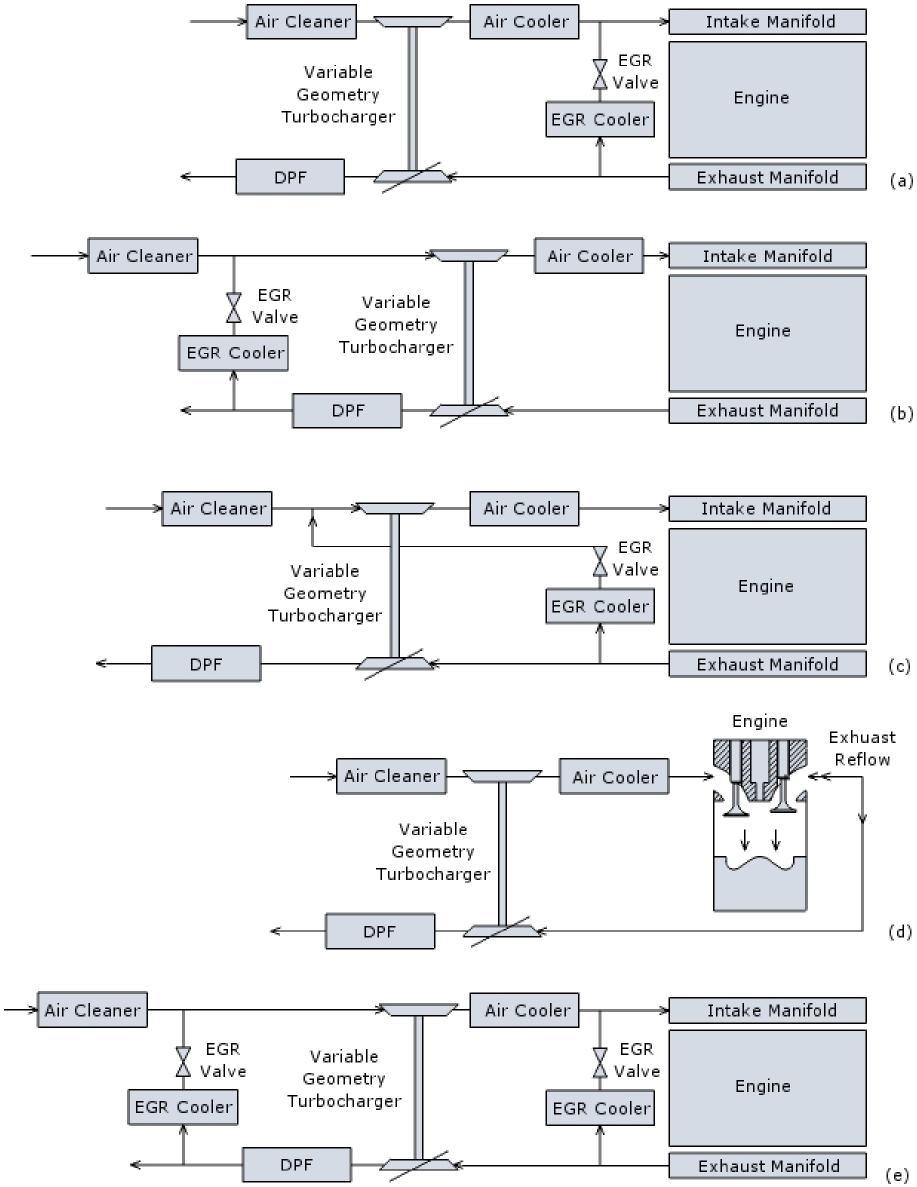


$$EGR(\%) = \frac{[CO_2]_{intake\,manifold} - [CO_2]_{ambient}}{[CO_2]_{exhaust\,manifold} - [CO_2]_{ambient}} \times 100$$





Exhaust Gas Recirculation



High pressure loop (HPL)

Low pressure loop (LPL)

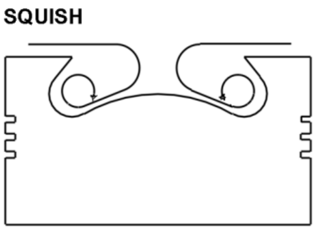
Hybrid

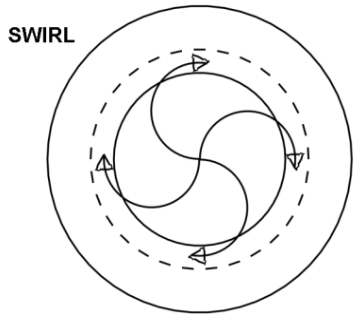
Internal

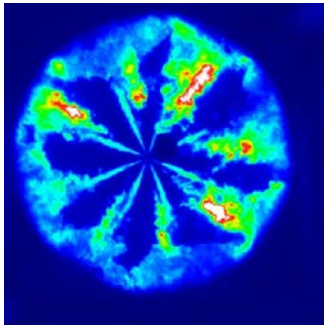
Dual HPL and LPL

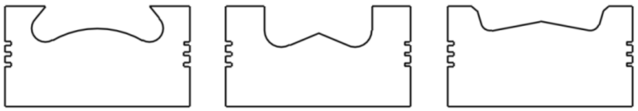
<u>Design factors</u>
Required temp reductions
Response time
Fouling/wear
Cost/size

Mixing and Charge Motion









Break up fuel spray – increase surface area contact and reduce PM formation
IDI engines – pre-chamber to promote charge mixing

<u>Swirl</u>

- Rotational motion from off centered intake valves or helical designs
    - Pumping losses
- Swirl ratio = air rotational speed / crankshaft rotational speed

<u>Squish</u>

- Turbulence created by piston bowl geometry when compressing near TDC
- Reentrant (toroidal) type piston bowls

Velocity of fuel spray also assists in mixing process

- multiple injection events used to aid late-stage mixing

Mixing and Charge Motion

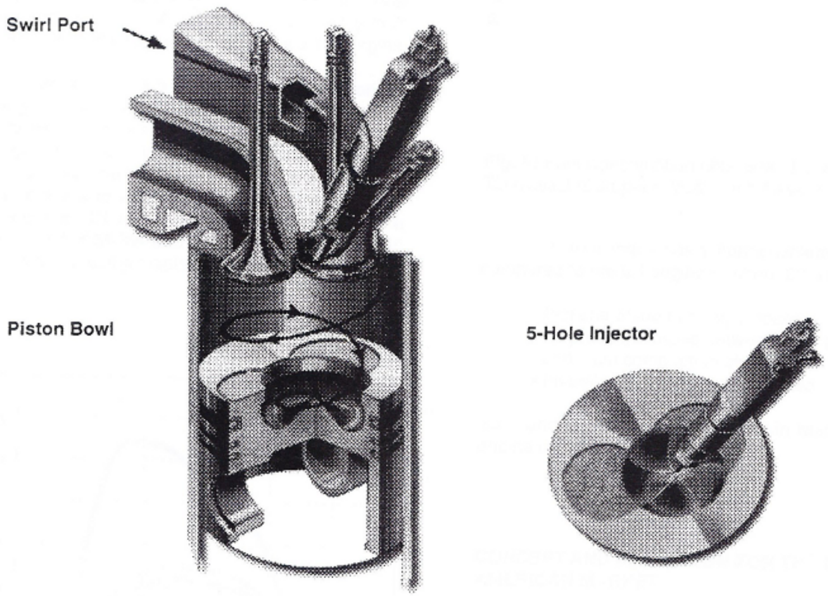
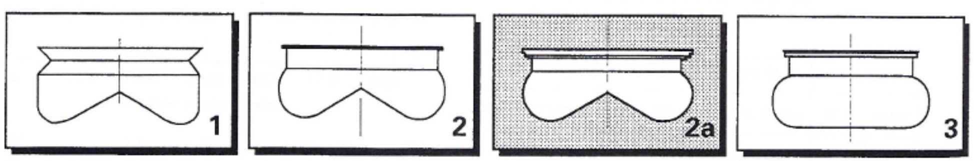


Fig. 6: Volkswagen-TDI-Combustion-System



The illustrated piston bowls were tested.
Bowl 2a represents the optimum under the given limiting conditions.

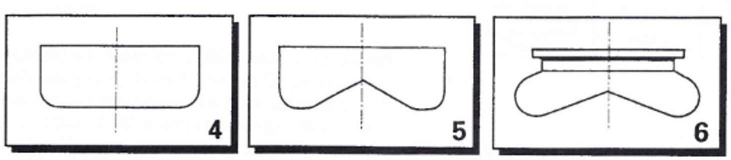


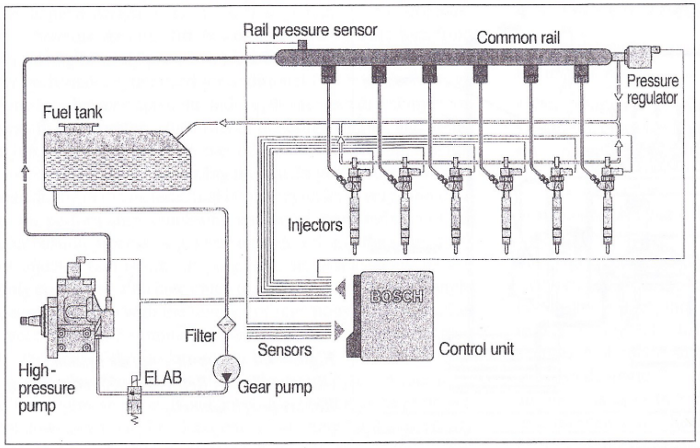
Fig. 7: Different Combustion Bowl Shapes 2138

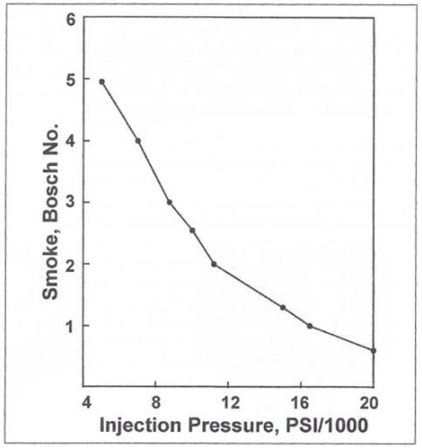
Active swirl control

- Throttling valve in intake port
- Variable Valve Actuation (VVA)

Fuel Delivery Systems

- **Higher injection pressures! (30,000 psi and up)**
  - Promote finer atomization of fuel
    - Increased surface area contact of fuel and oxygen
  - Increase penetration of fuel spray into chamber
    - Utilize more chamber space (ie. air) during combustion
    - Enable higher compression ratios
  - Recoup fuel economy losses from NO_x control strategies
- **Constant rail**
  - Diesel fuel "on-Demand"
    - Enable multiple injections and rate shaping
    - Allow ECU to control injection parameters / combustion



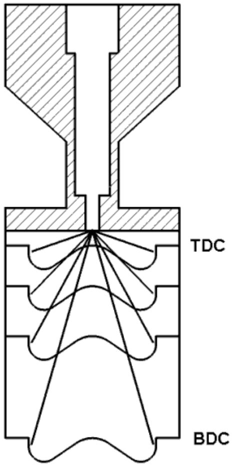


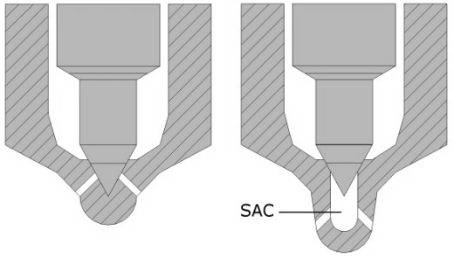
Fuel Injector Design

- Diameter and length of nozzle holes effect the spray properties
    - Generally, finer hole = fine atomization of fuel, lower PM emissions

- Spray angle must coordinate with piston bowl geometry
    - Prevent impingement of fuel on cylinder walls
    - Multiple spray angle injectors can coordinate with multiple injections and increase fuel penetration

- Reduce fuel leakage and HC emissions
    - Prevent unwanted needle valve bounce (after-injection)
    - Reduced Sac volume in injector tip / sealing needles





Injection Timing and Rate Shaping

Generally

Delayed injection

- Shortened ignition delay → reduced mixing
- As piston passes TDC, cylinder volume expands
  - Drop in temperature and pressure reduces peak flame temps
- Reduce NO formation at expense of PM and fuel consumption

Advanced injection

- Cylinder not up to temp → extended ignition delay
- More mixing of fuel and air before combustion → leaner mixtures → increase NO, decrease PM
  - over advancement, fuel impingement on cylinder walls

Injection Timing and Rate Shaping

Multiple injections

Traditional 3-stage injection process

1) Pre injection as piston approaches TDC
   - Gradually increase cylinder temperature
     - minimize sudden combustion events
   - Reduce engine-knocking noise and component stresses

2) Main injection
   - Deliver useful work

3) Post injection
   - Raise temperature of exhaust gas for aftertreatment devices

More injections used frequently

Rate shaping

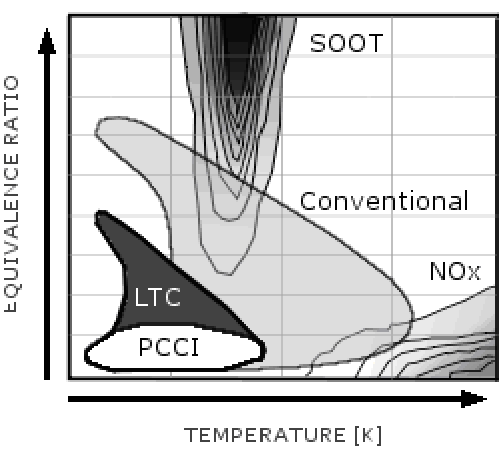
-Vary rate of fuel injection in response to engine parameters

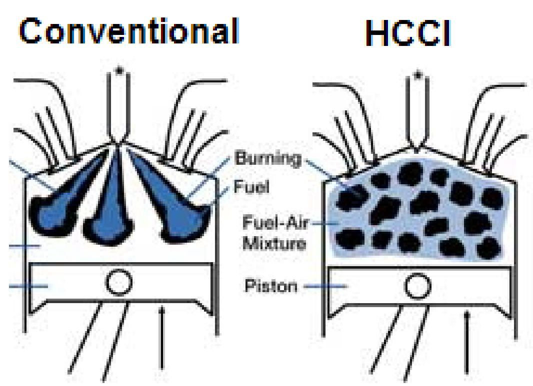
-Smooth multiple injections into “ideal” spray

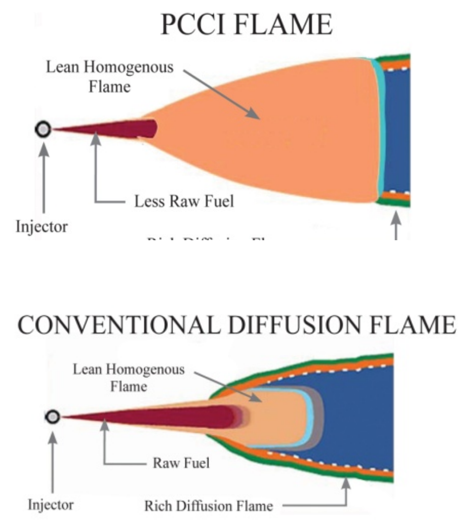
Other Technologies

Homogeneous and Premixed charge compression ignition (HCCI, PCCI)

- PCCI subset of HCCI
- Multiple early injections (much more fuel than pilot injections) + high EGR
  - simultaneous reductions in PM and NO_x
  - Difficult to control ignition timing, knocking / noise
  - Reduced operating range (torque/speed)
    - Integrated with diffusion flame combustion (**Mixed mode combustion**)
      - Need smooth transitions between combustion modes







Other Technologies

*** Enable emission reductions strategies by recouping thermal efficiency/fuel economy losses**

Materials science

- Enhanced strength of materials
  - ex. enable further increases in turbo boost and fuel injection pressures
  - ex. reduce the inertia and weight of engine components
- Improved cylinder and exhaust coatings
  - reduce heat rejection and improve thermal efficiencies
- Improvements in piston ring design and lubrication oil formulation
  - reduce oil consumption (OC/HC/Ash emissions)
  - reduce frictional drag on moving components and can minimize fuel and oil consumption

Energy recovery systems

- Turbocharging
- Turbocompounding – gear from turbocharger driveshaft to engine driveshaft
- Heat recovery systems
  - Thermoelectric generation in exhaust (5% or more in the short term)

Real World Considerations

Retrofit

- Upgrade kits may be available from some OEMs
    - http://www.epa.gov/otaq/retrofit/verif-list.htm
    - http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm

Rebuild

- May be most cost effective for high value equipment
- May also improve fuel economy and increase engine life

Repower

- Replace with new engine
- High cost, but may “solve” problem
    - http://www.epa.gov/otaq/certdata.htm
    - http://www.msha.gov/TECHSUPP/ACC/lists/lists.htm
- With new engines, maintenance for reduced emissions is always aimed at returning engine to its original tuning.

Questions?

Disclaimer

The findings and conclusions in this presentation are those of the authors and do not necessarily represent the views of NIOSH. Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention

Contact

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