Diesel injection, ignition, and fuel air mixing

1. Fuel spray phenomena
2. Spontaneous ignition
3. Effects of fuel jet and charge motion on mixing-controlled combustion
4. Fuel injection hardware
5. Challenges for diesel combustion

DIESEL FUEL INJECTION

The fuel spray serves multiple purposes:
- Atomization
- Fuel distribution
- Fuel/air mixing

Typical Diesel fuel injector
- Injection pressure: 1000 to 2200 bar
- 5 to 20 holes at ~ 0.12 - 0.2 mm diameter
- Drop size 0.1 to 10 μm
- For best torque, injection starts at about 20° BTDC

Injection strategies for NOx control
- Late injection (inj. starts at around TDC)
- Other control strategies:
  - Pilot and multiple injections, rate shaping, water emulsion
Diesel Fuel Injection System

(A Major cost of the diesel engine)
- Performs fuel metering
- Provides high injection pressure
- Distributes fuel effectively
  - Spray patterns, atomization etc.
- Provides fluid kinetic energy for charge mixing

Typical systems:
- Pump and distribution system (100 to 1500 bar)
- Common rail system (1000 to 1800 bar)
- Hydraulic pressure amplification
- Unit injectors (1000 to 2200 bar)
- Piezoelectric injectors (1800 bar)
- Electronically controlled

EXAMPLE OF DIESEL INJECTION

(Hino K13C, 6 cylinder, 12.9 L turbo-charged diesel engine, rated at 294KW@2000 rpm)
- Injection pressure = 1400 bar; duration = 40°CA
- BSFC 200 g/KW-hr
- Fuel delivered per cylinder per injection at rated condition
  - 0.163 gm ~0.21 cc (210 mm³)
- Averaged fuel flow rate during injection
  - 64 mm³/ms
- 8 nozzle holes, at 0.2 mm diameter
  - Average exit velocity at nozzle ~253 m/s
Typical physical quantities in nozzle flow

- Diesel fuel @ 100°C
  - s.g. ~ 0.78, μ ~ 5x10^-4 N-s/m²
- Nozzle diameter ~0.2 mm
- L/d ~ 5 to 10
- Reynolds No. ~ 10⁵ (turbulent)
- Pressure drop in nozzle
  ~30 bar << driving pressure (~1000 bar)
- Injection velocity

\[ u \approx \sqrt{\frac{2\Delta P}{\rho_{fuel}}} \approx 500 \text{ m/s @ } \Delta P \text{ of 1000 bar} \]

Fuel Atomization Process

- Liquid break up governed by balance between aerodynamic force and surface tension

  \[ \text{Webber Number (} W_b \text{)} = \frac{\rho_g u^2 d}{\sigma} \]

- Critical Webber number: \( W_{b,\text{critical}} \) ~ 30; diesel fuel surface tension ~ 2.5x10⁻² N/m

- Typical \( W_b \) at nozzle outlet > \( W_{b,\text{critical}} \): fuel shattered into droplets within ~ one nozzle diameter

- Droplet size distribution in spray depends on further droplet breakup, coalescence and evaporation
Droplet size distribution

\[ f(D) \, dD = \text{probability of finding particle with diameter in the range of (D, D + dD)} \]

\[ 1 = \int_0^\infty f(D) \, dD \]

Average diameter

\[ \bar{D} = \int_0^\infty f(D) \, D \, dD \]

Volume distribution

\[ \frac{1}{V} \, dV = \frac{f(D) \, D^3}{\int_0^\infty f(D) \, D^3 \, dD} \]

Sauter Mean Diameter (SMD)

\[ D_{32} = \frac{\int_0^\infty f(D) \, D^3 \, dD}{\int_0^\infty f(D) \, D^2 \, dD} \]

Fig. 10.28 Droplet size distribution measured well downstream; numbers on the curves are radial distances from jet axis. Nozzle opening pressure at 10 MPa; injection into air at 11 bar.
Droplet Behavior in Spray

- Small drops (~ micron size) follow gas stream; large ones do not
  - Relaxation time $\tau \propto d^2$
- Evaporation time $\propto d^2$
  - Evaporation time small once charge is ignited
- Spray angle depends on nozzle geometry and gas density: $\tan(\theta/2) \propto \sqrt{\rho_{\text{gas}}/\rho_{\text{liquid}}}$
- Spray penetration depends on injection momentum, mixing with charge air, and droplet evaporation

Spray Penetration: vapor and liquid (Fig. 10-20)

© McGraw-Hill Education. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use.
Auto-ignition Process

PHYSICAL PROCESSES (Physical Delay)
- Drop atomization
- Evaporation
- Fuel vapor/air mixing

CHEMICAL PROCESSES (Chemical Delay)
- Chain initiation
- Chain propagation
- Branching reactions

CETANE IMPROVERS
- Alkyl Nitrates
  - 0.5% by volume increases CN by ~10

Mixture cooling from heat of vaporization

Adiabatic, constant pressure evaporation
Dodecane in air
Initial condition:
- Air at 800 K, 80 bar
- Liq. dodecane at 350K, 80 bar
**Ignition Mechanism: similar to SI engine knock**

**CHAIN BRANCHING EXPLOSION**

Chemical reactions lead to increasing number of radicals, which leads to rapidly increasing reaction rates

<table>
<thead>
<tr>
<th>Chain Initiation</th>
<th>Formation of Branching Agents</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH + O₂ ⇒ R + HO₂</td>
<td>R'O₂ + RH ⇒ ROOH + R</td>
</tr>
<tr>
<td>Chain Propagation</td>
<td>Degenerate Branching</td>
</tr>
<tr>
<td>R + O₂ ⇒ R'O₂, etc.</td>
<td>ROOH ⇒ R'O + OH</td>
</tr>
<tr>
<td></td>
<td>R'CHO + O₂ ⇒ R'CO + HO₂</td>
</tr>
</tbody>
</table>

**Cetane Rating**

(Procedure is similar to Octane Rating for SI Engine; for details, see 10.6.2 of text)

**Primary Reference Fuels:**
- Normal cetane (C₁₆H₃₄): CN = 100
- Hepta-Methyl-Nonane (HMN; C₅₁₆H₃₄): CN = 15  
  (2-2-4-4-6-8-8 Heptamethylnonane)

**Rating:**
- Operate CFR engine at 900 rpm with fuel
- Injection at 13° BTC
- Adjust compression ratio until ignition at TDC
- Replace fuel by reference fuel blend and change blend proportion to get same ignition point
- CN = % n-cetane + 0.15 x % HMN
Ignition delays measured in a small four-stroke cycle DI diesel engine with \( r_c = 16.5 \), as a function of load at 1980 rpm, at various cetane number (Fig. 10-36)

Fuel effects on Cetane Number (Fig. 10-40)

- Adding more stable species
  - \( n \)-paraffins
  - Isoalkanes
  - Cycloalkanes
  - Aromatics

- Adding less stable species
  - \( n \)-pentane
  - 2,7-dimethyloctane
  - 50\% 3,4-dimethyldecane
  - 50\% 3,3-dimethyloctane

© McGraw-Hill Education. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use.
**Ignition Delay Calculations**

- Difficulty: do not know local conditions (species concentration and temperature) to apply kinetics information

Two practical approaches:

- Use an "instantaneous" delay expression
  \[ \tau(T,P) = P^{-n}\exp(-E_A/T) \]
  and solve ignition delay (\( \tau_{id} \)) from
  \[ 1 = \int_{\tau_{si}}^{\tau_{si} + \tau_{id}} \frac{1}{\tau(T(t),P(t))} \, dt \]

- Use empirical correlation of \( \tau_{id} \) based on T, P at an appropriate charge condition; e.g. Eq. (10.37 of text)
  \[ \tau_{id}(CA) = (0.36 + 0.22S_p(m/s))\exp\left[E_A\left(\frac{1}{RT(K)} - \frac{1}{17190}\right) + \left(\frac{21.2}{P(bar) - 12.4}\right)^{0.63}\right] \]
  \[ E_A \text{ (Joules per mole)} = \frac{618,840}{(CN+25)} \]

**Diesel Engine Combustion**

**Air Fuel Mixing Process**

- Importance of air utilization
  - Smoke-limit A/F ~ 20
- Fuel jet momentum / wall interaction has a larger influence on the early part of the combustion process
- Charge motion impacts the later part of the combustion process (after end-of-injection)

**CHARGE MOTION CONTROL**

- Intake created motion: swirl, etc.
  - Not effective for low speed large engine
- Piston created motion - squish
Interaction of fuel jet and the chamber wall

Sketches of outer vapor boundary of diesel fuel spray from 12 successive frames (0.14 ms apart) of high-speed shadowgraph movie. Injection pressure at 60 MPa.

Fig. 10-21

Interaction of fuel jet with air swirl

Schematic of fuel jet – air swirl interaction; $\phi$ is the fuel equivalence ratio distribution

Fig. 10-22
RATE OF HEAT RELEASE IN DIESEL COMBUSTION

(Fig. 10.8 of Text)

Part of combustion affected most by the charge motion

DIESEL FUEL INJECTION HARDWARE

• High pressure system
  – precision parts for flow control
• Fast action
  – high power movements

Expensive system
FUEL METERING AND INJECTION SYSTEM - CONCEPT

Process:
- Fill
- Pressurize
- Inject
- Spill

Fuel Delivery Control

Fig. 3: Plunger-stroke phases

1. Bottom dead center (BDC)
2. Prestroke
3. Retraction stroke
4. Effective stroke
5. Residual stroke
6. Top dead center (TDC)

Fuel flows from the injection pump's fuel gallery and into the high-pressure chamber of the plunger and barrel assembly.

© Robert Bosch GmbH. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use.
Injection pressure

- Positive displacement injection system
  - Injection pressure adjusted to accommodate plunger motion
  - Injection pressure \( \propto \text{rpm}^2 \)

- Injection characteristics speed dependent
  - Injection pressure too high at high rpm
  - Injection pressure too low at low rpm
Nozzle opening speed controlled by the flow rate difference between the Bleed (6) and Feed (7) orifices

From Bosch: Diesel Engine Management
Caterpillar Hydraulic Electronic Unit Injector (HEUI)

Fuel line: 200kPa; Low pressure oil: 300 kPa; High pressure oil: up to 23 MPa; Intensifier area ratio 7:1 Injection pressure up to 150 MPa

© Society of Automotive Engineers. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use.

Piezoelectric injectors

- For both diesel and GDI applications
- Up to 180 MPa injection pressure
- 5 injections per cycle
- In vehicle production already
- Suppliers: Bosch; Delphi; Denso; Siemens; ...

© Robert Bosch GmbH. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use.
Split Injection (SAE Paper 940668)

1600 rpm, 184 KPa manifold pressure, overall fuel equivalence ratio = 0.45;
CHALLENGES IN DIESEL COMBUSTION

Heavy Duty Diesel Engines
• NOx emission
• Particulate emission
• Power density
• Noise

High Speed Passenger Car Diesel Engines
• All of the above, plus
  – Fast burn rate

Cavitation in Injection Nozzle

• Cavitation happens when local pressure is lower than the fluid vapor pressure
• Effects
  – Discharge rate
  – Affects the spray angle
  – Damage to the nozzle passage
• Factors affecting cavitation
  – Combustion chamber pressure
  – Local streamline curvature within the nozzle
Flow process that leads to cavitation

Bernoulli drop
$$\Delta P_b = \frac{1}{2} \rho_f (u_1^2 - u_2^2)$$
$$= \frac{1}{2} \rho_f u_2^2 \left[ \left( \frac{A_2}{A_1} \right)^2 - 1 \right]$$
$$\approx P_{inj} \left[ \left( \frac{A_2}{A_1} \right)^2 - 1 \right]$$

Further friction drop $$\Delta P_f$$

Combustion chamber pressure $$P_c$$

Cavitation occurs if $$P_{min} \leq$$ fuel saturation pressure

Flow separation (recirculation region)
Flow reattachment

Pressure drop $$\Delta P$$

Flow separation (recirculation region)
Flow reattachment