2.61 Internal Combustion Engines
Spring 2008

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 ~ 0.15 - 0.2 mm diameter
- Drop size 0.1 to 10 μm
- For best torque, injection starts at about 20^o 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 1700 bar)
- Hydraulic pressure amplification
- Unit injectors (1000 to 2500 bar)
- Piezoelectric injectors (to 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^{o}CA
- BSFC 200 g/KW-hr
- Fuel delivered per cylinder per injection at rated condition
  - 0.163 gm ~0.21 cc (210 mm^3)
- Averaged fuel flow rate during injection
  - 64 mm^3/ms
- 8 nozzle holes, at 0.2 mm diameter
  - Average exit velocity at nozzle ~253 m/s

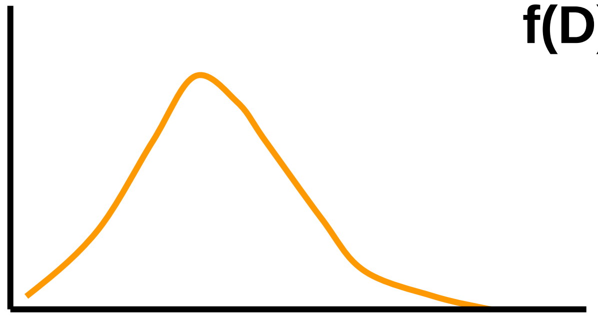
Fuel Atomization Process

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

$$\text{Webber Number } (W_b) = \frac{\rho_{gas} u^2 d}{\sigma}$$

- Critical Webber number: $W_{b,critical}$ ~ 30; diesel fuel surface tension ~ 2.5×10^{-2} N/m
- Typical W_b at nozzle outlet > $W_{b,critical}$; fuel shattered into droplets within ~ one nozzle diameter
- Droplet size distribution in spray depends on further droplet breakup, coalescence and evaporation

Droplet size distribution



Size distribution:

f(D)dD = probability of finding particle with diameter in the range of (D, D + dD)

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

Average diameter

$$\overline{D} = \int_0^\infty f(D)\,D\,dD$$

Volume distribution

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

Sauter Mean Diameter (SMD)

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

Droplet Size Distribution

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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 : $\tan(\theta/2) \propto \sqrt{(\rho_{gas}/\rho_{liquid})}$
- Spray penetration depends on injection momentum, mixing with charge air, and droplet evaporation

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

Shadowgraph image showing both liquid and vapor penetration

Back-lit image showing liquid-containing core

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

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

<u>Chain Initiation</u>

$$RH + O_2 \Rightarrow \dot{R} + H\dot{O}_2$$

<u>Chain Propagation</u>

$$\dot{R} + O_2 \Rightarrow R\dot{O}_2, \text{etc.}$$

<u>Formation of Branching Agents</u>

$$R\dot{O}_2 + RH \Rightarrow ROOH + \dot{R}$$

$$R\dot{O}_2 \Rightarrow R'CHO + R''\dot{O}$$

<u>Degenerate Branching</u>

$$ROOH \Rightarrow R\dot{O} + \dot{O}H$$

$$R'CHO + O_2 \Rightarrow R'\dot{C}O + H\dot{O}_2$$

Cetane Rating

(Procedure is similar to Octane Rating for SI Engine; for details, see10.6.2 of text)

Primary Reference Fuels:

- Normal cetane ($C_{16}H_{34}$): CN = 100
- Hepta-Methyl-Nonane (HMN; $C_{16}H_{34}$): CN = 15
  (2-2-4-4-6-8-8 Heptamethylnonane)

Rating:

- Operate CFR engine at 900 rpm with fuel
- Injection at 13^o 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 Delay

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Ignit on 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)

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 (τ_{id}) from

$$1 = \int_{t_{si}}^{t_{si}+\tau_{id}} \frac{1}{\tau(T(t),P(t))}\,dt$$

- Use empirical correlation of τ_{id} based on T, P at an appropriate charge condition; e.g. Eq. (10.37 of text)

$$\tau_{id}(CA) = (0.36 + 0.22\overline{S}_p(m/s))\exp\left[E_A\left(\frac{1}{\tilde{R}T(K)} - \frac{1}{17190}\right) + \left(\frac{21.2}{P(bar) - 12.4}\right)^{0.63}\right]$$

E_A (Joules per mole) = 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

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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; Φ is the fuel equivalence ratio distribution

Fig. 10-22

Rate of Heat Release in Diesel Combustion

(Fig. 10.8 of Text)

DIESEL FUEL INJECTION HARDWARE

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

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Expensive system

Injection pressure

- Positive displacement injection system
  - Injection pressure adjusted to accommodate plunger motion
  - Injection pressure $\propto$ rpm^2
- Injection characteristics speed dependent
  - Injection pressure too high at high rpm
  - Injection pressure too low at low rpm

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