Diesel Engine Combustion

1. Characteristics of diesel combustion
2. Different diesel combustion systems
3. Phenomenological model of diesel combustion process
4. Movie of combustion in diesel systems
5. Combustion pictures and planar laser sheet imaging

DIESEL COMBUSTION PROCESS

- Liquid fuel injected into compressed charge
- Fuel evaporates and mixes with the hot air
- Auto-ignition with the rapid burning of the fuel-air that is “premixed” during the ignition delay period
  - Premixed burning is fuel rich
- As more fuel is injected, the combustion is controlled by the rate of diffusion of air into the flame
NATURE OF DIESEL COMBUSTION

- Heterogeneous
  - liquid, vapor and air
  - spatially non-uniform
- turbulent
- diffusion flame
  - High temperature and pressure
  - Mixing limited

The Diesel Engine

- Intake air not throttled
  - Load controlled by the amount of fuel injected
    > A/F ratio: idle ~ 80
    > Full load ~19 (less than overall stoichiometric)
- No “end-gas”; avoid the knock problem
  - High compression ratio: better efficiency
- Combustion:
  - Turbulent diffusion flame
  - Overall lean
Diesel as the Most Efficient Power Plant

- Theoretically, for the same CR, SI engine has higher $\eta_f$; but diesel is not limited by knock, therefore it can operate at higher CR and achieves higher $\eta_f$
- Not throttled - small pumping loss
- Overall lean - higher value of $\gamma$ - higher thermodynamic efficiency
- Can operate at low rpm - applicable to very large engines
  - slow speed, plenty of time for combustion
  - small surface to volume ratio: lower percentage of parasitic losses (heat transfer and friction)
- Opted for turbo-charging: higher energy density
  - Reduced parasitic losses (friction and heat transfer) relative to output

Large Diesels: $\eta \approx 55$
$\approx 98\%$ ideal efficiency!

Diesel Engine Characteristics
(compared to SI engines)

- Better fuel economy
  - Overall lean, thermodynamically efficient
  - Large displacement, low speed – lower FMEP
  - Higher CR
    - CR limited by peak pressure, NOx emissions, combustion and heat transfer loss
  - Turbo-charging not limited by knock: higher BMEP over domain of operation, lower relative losses (friction and heat transfer)
- Lower Power density
  - Overall lean: would lead to smaller BMEP
  - Turbocharged: would lead to higher BMEP
    - not knock limited, but NOx limited
    - BMEP higher than naturally aspirated SI engine
  - Lower speed: overall power density ($P/V_D$) not as high as SI engines
- Emissions: more problematic than SI engine
  - NOx: needs development of efficient catalyst
  - PM: regenerative and continuous traps
Typical SI and Diesel operating value comparisons

- **BMEP**
  - Naturally aspirated: 10-15 bar, 10 bar
  - Turbo: 15-25 bar, 15-25 bar

- **Power density**
  - Naturally aspirated: 50-70 KW/L, 20 KW/L
  - Turbo: 70-120 KW/L, 40-70 KW/L

- **Fuel**
  - H to C ratio: CH$_{1.87}$, CH$_{1.80}$
  - Stoichiometric A/F: 14.6, 14.5
  - Density: 0.75 g/cc, 0.81 g/cc
  - LHV (mass basis): 44 MJ/kg, 43 MJ/kg
  - LHV (volume basis): 3.30 MJ/L, 3.48 MJ/L (5.5% higher)
  - LHV (CO$_2$ basis): 13.9 MJ/kgCO$_2$, 13.6 MJ/kgCO$_2$ (2.2% lower)

Disadvantages of Diesel Engines

- Cold start difficulty
- Noisy - sharp pressure rise: cracking noise
- Inherently slower combustion
- Lower power to weight ratio
- Expensive components
- NO$_x$ and particulate matters emissions
Market penetration

- **Diesel driving fuel economy ~ 30% better than SI**
  - 5% from fuel energy/volume
  - 15% from eliminating throttle loss
  - 10% from thermodynamics
    - 2nd law losses (friction and heat transfer)
    - Higher compression ratio
    - Higher specific heat ratio

- **Dominant world wide heavy duty applications**
- **Dominant military applications**
- **Significant market share in Europe**
  - Tax structure for fuel and vehicle
- **Small passenger car market fraction in US and Japan**
  - Fuel cost
  - Customer preference
  - Emissions requirement

Applications

- **Small** (7.5 to 10 cm bore; previously mainly IDI; new ones are high speed DI)
  - passenger cars
- **Medium** (10 to 20 cm bore; DI)
  - trucks, trains
- **Large** (30 to 50 cm bore; DI)
  - trains, ships
- **Very Large** (100 cm bore)
  - stationary power plants, ships
Common Direct-Injection Compression-Ignition Engines
(Fig. 10.1 of text)

(a) Quiescent chamber with multihole nozzle typical of larger engines
(b) Bowl-in-piston chamber with swirl and multihole nozzle; medium to small size engines
(c) Bowl-in-piston chamber with swirl and single-hole nozzle; medium to small size engines

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Common types of small Indirect-injection diesel engines
(Fig. 10.2 of text)

(a) Swirl prechamber
(b) Turbulent prechamber

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## Common Diesel Combustion Systems (Table 10.1)

<table>
<thead>
<tr>
<th>System</th>
<th>Direct Injection</th>
<th>Indirect Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quiescent</td>
<td>Medium swirl “M”</td>
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<tr>
<td>Size</td>
<td>Largest</td>
<td>Medium - small</td>
</tr>
<tr>
<td>Cycle</td>
<td>2/4-stroke</td>
<td>2-stroke</td>
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<tr>
<td>Turbocharged/ supercharged/ naturally aspirated</td>
<td>TC/TC/TC/NA</td>
<td>TC/NA/NA/TC</td>
</tr>
<tr>
<td>Maximum speed, rpm/min</td>
<td>900-150</td>
<td>150-100</td>
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<tr>
<td>Stroke/bore</td>
<td>3.5-1.2</td>
<td>1.3-1.0</td>
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<tr>
<td>Compression ratio</td>
<td>12-15</td>
<td>15-16</td>
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<tr>
<td>Chamber</td>
<td>Open or shallow dish</td>
<td>Bowl-in-piston</td>
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<tr>
<td>Air-flow pattern</td>
<td>Quiescent</td>
<td>Medium swirl “M”</td>
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<tr>
<td>Number of nozzle holes</td>
<td>Multi</td>
<td>Multi</td>
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<tr>
<td>Injection pressure</td>
<td>Very high</td>
<td>High</td>
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### Effect of Engine Size

![Effect of Engine Size](image)

- **DI engines**
- **IDI Engines**
- **SI Engine**

(Values at best efficiency point of engine map)
Typical Large Diesel Engine Performance Diagram

Sulzer RLB 90 - MCR 1
Turbo-charged 2-stroke Diesel

- 1.9 m stroke; 0.9 m bore

Rating:
- Speed: 102 Rev/ min
- Piston speed 6.46 m/s
- BMEP: 14.3 bar

Configurations
- 4 cyl: 11.8 MW (16000 bhp)
- 5 cyl: 14.7 MW (20000 bhp)
- 6 cyl: 17.7 MW (24000 bhp)
- 7 cyl: 20.6 MW (28000 bhp)
- 8 cyl: 23.5 MW (32000 bhp)
- 9 cyl: 26.5 MW (36000 bhp)
- 10 cyl: 29.4 MW (40000 bhp)
- 12 cyl: 35.3 MW (48000 bhp)

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Diesel combustion process — direct injection

1) Ignition delay — no significant heat release
2) "Premixed" rapid combustion
3) "Mixing controlled" phase of combustion
4) "Late" combustion phase

Note:
(2) is too fast;
(4) is too slow

Rate of Heat Release in Diesel Combustion
(Fig. 10.8 of Text)

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A Simple Diesel Combustion Concept (Fig. 10-8)

Visualization of Diesel Combustion

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FEATURES OF DIESEL COMBUSTION

- **Ignition delay**
  - Auto-ignition in different parts of combustion chamber

- **After ignition, fuel sprays into hot burned gas**
  - Then, evaporation process is fast

- **Major part of combustion controlled by fuel air mixing process**
  - Mixing dominated by flow field formed by fuel jet interacting with combustion chamber walls during injection

- **Highly luminous flame:**
  - Substantial soot formation in the fuel rich zone by pyrolysis, followed by substantial subsequent oxidation
Imaging of Diesel Combustion by Laser Sheet Illumination

Rayleigh scattering
Laser Induced Florescence
reflection from molecules

Fuel Equivalence Ratio

- Obtained by Planar Rayleigh scattering
- Substantial reduction of fuel equivalence ratio in the 'premixed' region indicates fuel-rich oxidation

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Oxidation occurs at the edge of the air and fuel rich region.

5.0° ASI
5.5° ASI
6.0° ASI
6.5° ASI
7.0° ASI
7.5° ASI
8.0° ASI
8.5° ASI
9.0° ASI
9.5° ASI

(Dash lines in the first two frames marks the vapor boundary of the fuel jet)

(Elastic scattering)

LII
Elastic scattering

Image of the Particulates

Laser Induced Incandescence
(signal ~ d³; observe small particles)

Elastic scattering
(signal ~ d⁶; observe large particles)

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Diesel Ignition, Premixed Burning and Transition into Diffusion Burning

- Premixed burning
  - Release of energy from fuel rich combustion
- Diffusion burning
  - Oxidation of incomplete products of the rich premixed combustion and fuel vapor at the jet-air interface

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