Chapter 5 Fuel Systems - Part 1

ME419 Thermal Systems Design
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Air Flow

\[ \frac{p_2^*}{p_1} = \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma-1}} \]

which is equal to 0.5283 for \( \gamma = 1.4 \)

\[ h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2} \]

\[ \dot{m}_a = \frac{p_1 \cdot A \cdot C_a}{\sqrt{T_1}} \sqrt{\frac{2\gamma}{R (\gamma - 1)}} \sqrt{\left( \frac{p_2}{p_1} \right)^{\frac{2}{\gamma}} - \left( \frac{p_2}{p_1} \right)^{\frac{\gamma+1}{\gamma}}} \]

\[ \dot{m}_a = \frac{p_1 \cdot A \cdot C_a}{\sqrt{T_1}} \sqrt{\frac{\gamma \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}}{R}} \]
Fuel Flow

\[ v_2 = \sqrt{\frac{2}{\rho_f}} (p_1 - p_2) \]

\[ \dot{m}_f = A \cdot C_f \sqrt{2 \rho_f (p_1 - p_2)} \]

Figure 5.2: Fuel flow, cylinder pressure and injection pressure in a unit injector for a 2-liter per cylinder diesel engine. [56]
Diesel: What and Why

1. Utilizes heavy fuel blends, less expensive(?)
2. Fuel has higher heating value on a volumetric basis
3. More efficient at part load
4. Higher compression ratio
5. Sturdier construction, more expensive
6. Lower speed
7. Higher torque, lower horsepower ratings
8. No spark system, rugged operation (?)
9. Problematic starting, particularly in cold weather
10. Characteristic odor
MAN Diesel SE (formerly MAN B&W Diesel AG)

Cummins

Caterpillar
Classifications and Considerations

1. Size (bore, stroke, number of cylinders, torque, speed, horsepower output, etc.)
2. Combustion chamber type (DI or IDI)
3. Two stroke, four stroke
4. Naturally aspirated, turbocharged
5. Fuel delivery system (low pressure and high pressure fuel metering)
6. Injector type (electronic, mechanical)
7. Spray pattern, spray penetration, droplet distribution
8. Rate of fuel delivery
9. Heat release of fuel
DI or IDI?

FIGURE 10-1
Common types of direct-injection compression-ignition or diesel engine combustion systems: (a) quiescent chamber with multi-hole nozzle typical of larger engines; (b) bowl-in-piston chamber with swirl and multi-hole nozzle; (c) bowl-in-piston chamber with swirl and single-hole nozzle. (b) and (c) used in medium to small DI engine size range.

FIGURE 10-2
Two common types of small indirect-injection diesel engine combustion systems: (a) swirl prechamber; (b) turbulent prechamber.
<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</td>
</tr>
<tr>
<td>Size</td>
<td>Largest</td>
<td>Medium</td>
</tr>
<tr>
<td>Cycle</td>
<td>2-/4-stroke</td>
<td>4-stroke</td>
</tr>
<tr>
<td>Turbocharged/supercharged/naturally aspirated</td>
<td>TC/NA</td>
<td>TC/NA</td>
</tr>
<tr>
<td>Maximum speed, rev/min</td>
<td>120–2100</td>
<td>1800–3500</td>
</tr>
<tr>
<td>Bore, mm</td>
<td>900–150</td>
<td>150–100</td>
</tr>
<tr>
<td>Stroke/bore</td>
<td>3.5–1.2</td>
<td>1.3–1.0</td>
</tr>
<tr>
<td>Chamber</td>
<td>Open or shallow dish</td>
<td>Bowl-in-piston</td>
</tr>
<tr>
<td>Air-flow pattern</td>
<td>Quiescent</td>
<td>Medium swirl</td>
</tr>
<tr>
<td>Number of nozzle holes</td>
<td>Multi</td>
<td>Multi</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>Very high</td>
<td>High</td>
</tr>
</tbody>
</table>
DI and IDI Comparisons

**DI Engines**
- larger bore
- turbocharged
- 2 or 4 stroke
- low speed
- lower compression ratio
- multi-hole injectors
- high pressure injection

**IDI Engines**
- smaller bore
- turbocharged
- 4 stroke
- high speed
- high compression ratio
- single hole injectors
- lower pressure injection
CI and SI Comparison

Figure 6.1
Comparison of the part-load efficiency of spark ignition and diesel engines at 2000 rpm (Stone, 1989b).
Fuel Delivery Types

- low pressure fuel metering
  - jerk pump
    - in line
    - rotary (distributive)
- high pressure fuel metering
  - common rail

Figure 6.17
Fuel injection system for a compression ignition engine.
Common Rail

Figure 6.34
The key elements of a common rail injection system (courtesy of Lucas Diesel Systems).
Individual In-Line

note: This is a jerk pump with individual plungers. One plunger could also accomplish the task with some sort of fuel distribution system (a fuel distributor).
Individual Unit

Figure 5.4: An example of an electronically controlled unit injector. The start and end of injection are controlled by the solenoid valve.
Individual Unit - mechanical fuel metering
Pintle Nozzle

- High pressure inlet
- Leak of pipe
- Pressure adjusting shims
- Valve spring
- Lower spring plate
- Needle valve
- Nozzle body
- Annular fuel gallery
- Pintle type outlet
Injection Pressures and Fuel Lines

22000 psi
15000 psi

Fig 6-31 (left) CR – common rail, EUI – electronic unit injector, PLI – pump –line - injector system
Effect of Compressibility

Figure 5.10: Pressure pulses in an injection test rig operating on DME (left) and diesel fuel (right) with a valve opening pressure of 130 bar.
Heat Release

**FIGURE 10-9**
Typical DI engine heat-release-rate diagram identifying different diesel combustion phases.
Fuel Delivery and Pressure Development

![Graph showing cylinder pressure, rate of fuel injection, and net heat-release rate.]

**FIGURE 10-7**
Cylinder pressure $p$, rate of fuel injection $\dot{m}_f$, and net heat-release rate $\dot{Q}_h$ calculated from $p$ for small DI diesel engine, 1000 rev/min, normal injection timing, bmeq = 620 kPa.
Fuel Delivery and Pressure Development

- Ignition delay
- Premixed combustion phase
- Mixing controlled phase
- Late combustion phase
- Max cylinder pressure – about 1000 psi (7MPa = 7000 kPa = 70 atm)
- Fuel injection timing 20 deg BTDC
- Injection duration 20 deg
- Note vaporization before premixed combustion phase
Fuel Delivery and Heat Release

**FIGURE 10-8**
Schematic of relationship between rate of fuel injection and rate of fuel burning or energy release.⁶
Fuel Delivery and Heat Release

- Ignition delay
  - Physical
  - Chemical
- Engine Speed
- Engine Load
- Engine Temperature (cold start)
- Knocking in the CI engine
Heat Release

**FIGURE 10-10**
Schematic injection-rate and burning-rate diagrams in three different types of naturally aspirated diesel combustion system: (a) DI engine with central multihole nozzle; (b) DI “M”-type engine with fuel injected on wall; (c) IDI swirl chamber engine. Mechanisms A, B, and C defined in text.
Heat Release

- Fuel injection across chamber with substantial momentum (a)
- Fuel deposition on chamber walls, limited evaporation at the onset of injection, rate controlled by diffusion of gasses at wall during combustion (b,c)

**FIGURE 10-10**
Schematic injection-rate and burning-rate diagrams in three different types of naturally aspirated diesel combustion system: (a) DI engine with central multi-hole nozzle; (b) DI “M”-type engine with fuel injected on wall; (c) IDI swirl chamber engine. Mechanisms A, B, and C defined in text.
Ignition Delay

1. Injection timing – earlier injection causes increased ignition delay
2. Injection Quantity – higher load causes shorter injection delay
3. Intake air temp and pressure – increased temp and pressure shortens ignition delay
4. Engine speed – slight decrease in ignition delay
5. Wall effects – more fuel on walls increases ignition delay
6. Swirl - little effect
7. Oxygen concentration – increased oxygen levels, shorter ignition delay
8. Fuel properties – compact molecules increase ignition delay
Fuel Quality

- Percentage of good fuel blended by a fuel with low ignition quality – Cetane number
- Higher Cetane number fuels are less likely to knock (have short ignition delays)
- \[ CN = \% \text{ of } n\text{-cetane} + 0.15 \times \% \text{ HMN} \]
- Cetane = n- hexadecane
- HMN = heptamethylnonane
- Cetane number, like Octane number, higher the better, but for the opposite reason
Spray Characteristics

**FIGURE 10-19**
Schematic of diesel fuel spray defining its major parameters.\(^1\)

**FIGURE 10-20**
Shadowgraph and back-illuminated photographs of evaporating spray injected into nitrogen at 3.4 MPa and 670 K in rapid-compression machine. Times in milliseconds are after start of injection: injection duration 3.3 ms. Top (shadowgraph) photographs show full vapor and liquid region. Bottom (back-illuminated) photographs only show liquid-containing core.\(^2\)

**FIGURE 10-22**
Schematic of fuel spray injected radially outward from the chamber axis into swirling air flow. Shape of equivalence ratio (\(\phi\)) distribution within jet is indicated.
Spray Characteristics

1. Spray penetration
2. Spray angle
3. Droplet frequency distribution
4. Sauter mean diameter
Diesel Engine Emissions

- CO – not an issue (generally)
- CH$_x$ – sac volume, wall wetting, and incomplete combustion at high loads
  - controlled through better injector design, load limiting strategies, and exhaust treatment with catalysis
- NO$_x$ – bulk gases due to high temperature combustion of premixed fuel and droplet combustion
  - controlled through limited use of EGR and exhaust treatment with catalysis (SCR)
- particulate – agglomerated carbon particles from ‘improper’ combustion kinetics
  - controlled through injection timing, injection pressure, and exhaust treatment (filtration and regeneration).
NO\textsubscript{x} and Particulate

NO\textsubscript{x} formation in the premixed phase

NO\textsubscript{x} formation in the droplet phase

NO\textsubscript{x} – particulate tradeoff

FIGURE 10.9
Typical DI engine heat-release-rate diagram identifying different diesel combustion phases.
End