Lecture 38 – Diesel and dual cycles

Purdue ME 200, Thermodynamics I

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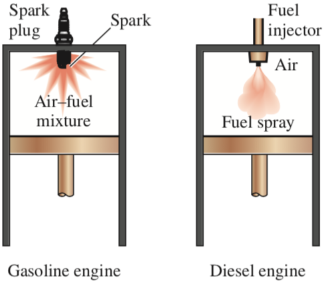
Outline

Gasoline and Diesel engines

- two types of reciprocating internal combustion engine:
  - spark-ignition (a.k.a. gasoline engines)
  - compression-ignition (a.k.a. Diesel engines)



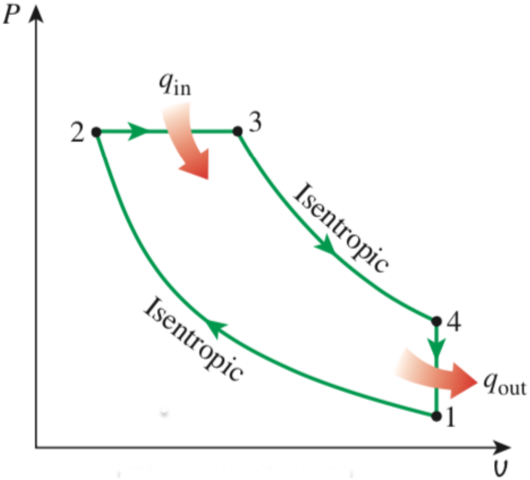
- Diesel engines aren't susceptible to knocking, so they can
  - reach higher compression ratios and efficiencies
  - use less refined (cheaper) fuels

Cengel and Boles, *Thermodynamics: An Engineering Approach* (2019)

The air-standard Diesel cycle

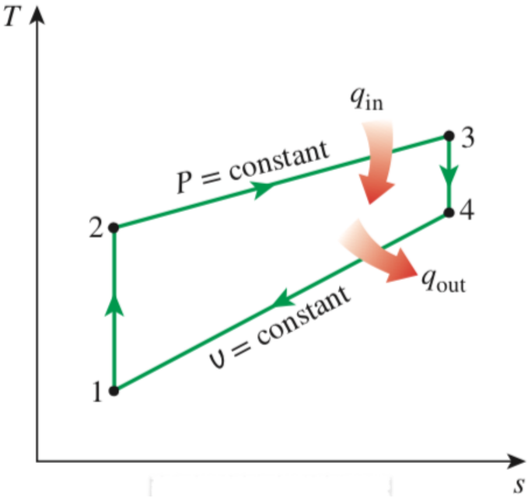
- the Otto cycle models an ideal spark-ignition engine
- the Diesel cycle models an ideal compression-ignition engine
- the Diesel cycle is almost identical to the Otto cycle
- but input heat transfer is at constant p rather than V

p-v diagram of the air-standard Diesel cycle



Cengel and Boles, *Thermodynamics: An Engineering Approach* (2019)

T-s diagram of the air-standard Diesel cycle



Cengel and Boles, *Thermodynamics: An Engineering Approach* (2019)

Energy balances in the air-standard Diesel cycle

- 3 Diesel energy balances look just like Otto:
  - ◇ input (compression) work: $W_{12} = m(u_2 - u_1)$
  - ◇ output (expansion) work: $W_{34} = m(u_3 - u_4)$
  - ◇ output (exhaust) heat transfer: $Q_{41} = m(u_4 - u_1)$
- but input (combustion) heat transfer is at constant p, so

$$W_{23} = \int_{V_2}^{V_3} p \mathrm{d}V = p_2(V_3 - V_2) = m(p_3 v_3 - p_2 v_2)$$

- and, from $\Delta U = m\Delta u = Q - W$,

$$\begin{aligned} Q_{23} &= m(u_3 - u_2) + W_{23} \\ &= m(u_3 + p_3 v_3 - [u_2 + p_2 v_2]) \\ &= m(h_3 - h_2) \end{aligned}$$

Air-standard Diesel cycle efficiency

- 1st law on the full system over a cycle ($\Delta U = 0$):

$$W_{12} + Q_{23} = W_{23} + W_{34} + Q_{41}$$

- so the air-standard Diesel cycle efficiency is

$$\begin{aligned}
\eta &= \frac{\text{net work output}}{\text{heat transfer input}} = \frac{W_{23} + W_{34} - W_{12}}{Q_{23}} \\
&= \frac{Q_{23} - Q_{41}}{Q_{23}} = 1 - \frac{Q_{41}}{Q_{23}} \\
\implies \eta &= 1 - \frac{u_4 - u_1}{h_3 - h_2}
\end{aligned}$$

Cold air-standard Diesel cycle efficiency

- in cold air-standard analysis, Diesel cycle efficiency is

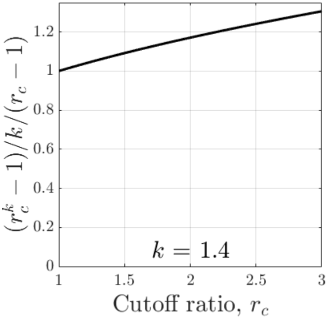
$$\eta = 1 - \frac{1}{r^{k-1}} \left[\frac{r_c^k - 1}{k(r_c - 1)} \right]$$

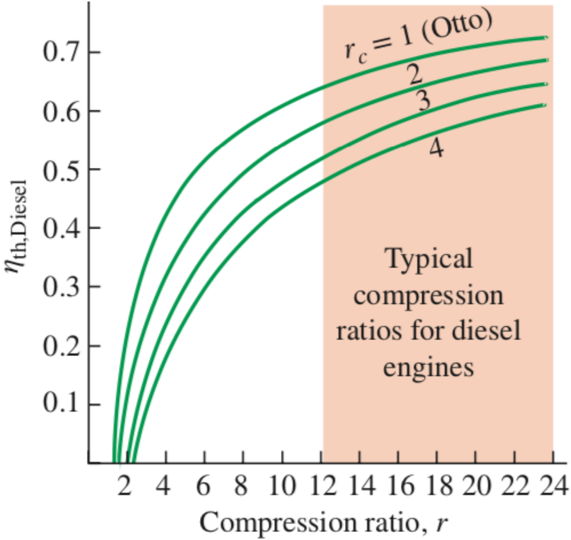
  (this comes from the polytropic ideal gas equations)
- in this formula,
  - $k = c_p/c_v$ is the (constant) specific heat ratio
  - $r = V_1/V_2$ is the compression ratio
  - $r_c = V_3/V_2$ is the **cutoff ratio**

Comparing Diesel and Otto cycle efficiencies

- consider cold air-standard Diesel and Otto cycles
- if both cycles have the same compression ratio, then

$$\eta_{\text{Diesel}} = 1 - \frac{1}{r^{k-1}} \underbrace{\left[\frac{r_c^k - 1}{k(r_c - 1)} \right]}_{\geq 1} \leq 1 - \frac{1}{r^{k-1}} = \eta_{\text{otto}}$$





Cengel and Boles, *Thermodynamics: An Engineering Approach* (2019)

Diesel and Otto cycle efficiencies (continued)

- for fixed compression ratio, Otto is more efficient than Diesel
- but Diesel engines aren't susceptible to knocking
- so they can reach higher compression ratios and efficiencies
- typical gasoline engine efficiency: 20–30%
- typical Diesel engine efficiency: 35–40%
- typical electric vehicle motor efficiency: 80–90%

Outline

The air-standard Diesel cycle

The air-standard dual cycle

Example

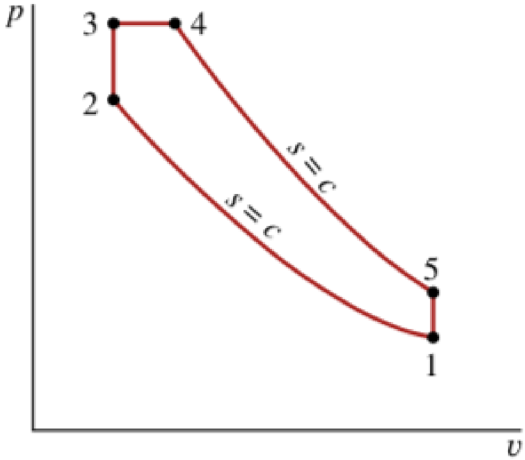
Otto and Diesel cycle reminders

- the Otto and Diesel cycles both involve four processes:
  - ◇ constant-entropy compression
  - ◇ input heat transfer
  - ◇ constant-entropy expansion
  - ◇ constant-volume output heat transfer
- input heat transfer is at constant V in Otto, p in Diesel

The air-standard dual cycle

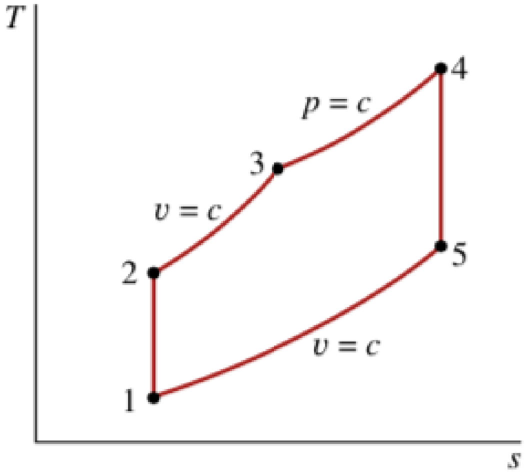
- the dual cycle is almost the same as Otto and Diesel
- but it breaks input heat transfer into two processes:
    1. input heat transfer at constant volume
    2. input heat transfer at constant pressure
- the dual cycle can model either gasoline or Diesel engines
- the added flexibility tends to improve model accuracy

Air-standard dual cycle p-v diagram



Moran et al., *Fundamentals of Engineering Thermodynamics* (2018)

Air-standard dual cycle T-s diagram



Moran et al., *Fundamentals of Engineering Thermodynamics* (2018)

Air-standard dual cycle energy balances

- constant-entropy compression:

$$Q_{12} = 0,\ W_{12} = m(u_2 - u_1)$$

- constant-volume input heat transfer:

$$Q_{23} = m(u_3 - u_2),\ W_{23} = 0$$

- constant-pressure input heat transfer:

$$Q_{34} = m(h_4 - h_3),\ W_{34} = p_3(v_4 - v_3)$$

- constant-entropy expansion:

$$Q_{45} = 0,\ W_{45} = m(u_4 - u_5)$$

- constant-volume output heat transfer:

$$Q_{51} = m(u_5 - u_1),\ W_{51} = 0$$

Air-standard dual cycle efficiency

- full-cycle energy balance:

$$W_{12} + Q_{23} + Q_{34} = W_{34} + W_{45} + Q_{51}$$

- so the air-standard dual cycle efficiency is

$$\begin{aligned}
\eta &= \frac{\text{net work output}}{\text{heat transfer input}} = \frac{W_{34} + W_{45} - W_{12}}{Q_{23} + Q_{34}} \\
&= \frac{Q_{23} + Q_{34} - Q_{51}}{Q_{23} + Q_{34}} \\
&= 1 - \frac{Q_{51}}{Q_{23} + Q_{34}}
\end{aligned}$$

$$\implies \eta = 1 - \frac{u_5 - u_1}{u_3 - u_2 + h_4 - h_3}$$

Outline

Problem statement

An air-standard Diesel cycle has the following property data:

state	T (K)	p (kPa)
1	300	100
2	898	5390
3	1797	5390
4	888	300

(a) Find the efficiency assuming varying specific heats.

(b) Find the compression ratio and cutoff ratio.

(c) Find the efficiency assuming constant specific heats.

Solution to part (a)

- with varying specific heats, the Diesel cycle efficiency is

$$\eta = 1 - \frac{u_4 - u_1}{h_3 - h_2}$$

- ideal gas table:
  - ◇ at $T_4 = 888$ K, $u_4 \approx 666.3$ kJ/kg
  - ◇ at $T_1 = 300$ K, $u_1 = 214.1$ kJ/kg
  - ◇ at $T_3 = 1797$ K, $h_3 \approx 2003$ kJ/kg
  - ◇ at $T_2 = 898$ K, $h_2 \approx 932.9$ kJ/kg
- plugging in numbers,

$$\eta = \cdots = 0.577$$

Solution to part (b)

- the compression ratio r and cutoff ratio r_c are

$$r = \frac{v_1}{v_2}, \;\; r_c = \frac{v_3}{v_2}$$

- we know p and T in all states, so the ideal gas law gives

$$v_1 = \frac{RT_1}{p_1} = \cdots = 0.861\mathrm{m}^3/\mathrm{kg}$$
$$v_2 = \frac{RT_2}{p_3} = \cdots = 0.048\mathrm{m}^3/\mathrm{kg}$$
$$v_3 = \frac{RT_3}{p_3} = \cdots = 0.096\mathrm{m}^3/\mathrm{kg}$$

- so $r = 18$ and $r_c = 2$

Solution to part (c)

- with constant specific heats, the Diesel cycle efficiency is

$$\eta = 1 - \frac{1}{r^{k-1}} \left[\frac{r_c^k - 1}{k(r_c - 1)} \right] = \cdots = 0.631$$

- with constant specific heats, we overestimate efficiency by

$$0.631 - 0.577 = 0.054$$

- this is $\sim$10% error relative to the true $\eta = 0.577$ (not great)