Lecture 37 – The Otto cycle

Purdue ME 200, Thermodynamics I

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Outline

Engine terminology

Two- and four-stroke engines

The air-standard assumptions

The air-standard Otto cycle

Gas power cycles

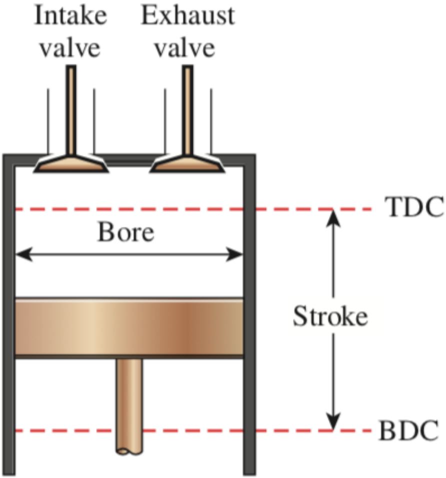
- in **vapor cycles**, the working fluid condenses and evaporates
- examples: the Rankine and vapor-compression cycles
- in **gas cycles**, the working fluid remains in the gas phase
- the next four lectures will cover gas power cycles
  - ◇ lectures 37–38: reciprocating internal combustion engines
  - ◇ lectures 39–40: gas turbine power plants

Reciprocating internal combustion engines

- an **engine** is a power cycle (usually one that moves stuff)
- **reciprocating** engines
    - have parts that move back and forth along a line
    - typically use a piston and cylinder
- **combustion** engines burn fuel for input heat transfer
    - **internal** combustion engines burn fuel inside the cylinder
    - **external** combustion engines burn fuel outside the cylinder
- most vehicles use reciprocating internal combustion engines

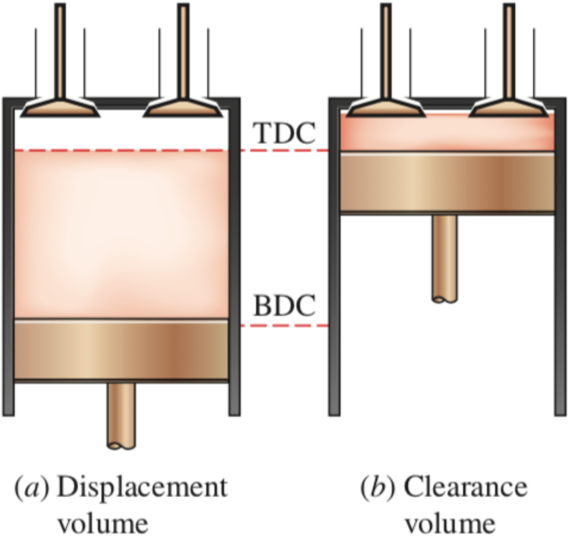
Spark-ignition and compression-ignition

- two types of reciprocating internal combustion engine:
    - **spark-ignition**
    - **compression-ignition**
- spark-ignition engines
    - use spark plugs to ignite the fuel-air mixture
    - are lighter, cheaper, and lower power
- compression-ignition engines
    - raise T and p high enough that the fuel-air mixture self-ignites
- the **Otto cycle** models an ideal spark-ignition engine
- the **Diesel cycle** models an ideal compression-ignition engine



- **top dead center** (TDC) is the lowest-volume state
- **bottom dead center** (BDC) is the highest-volume state

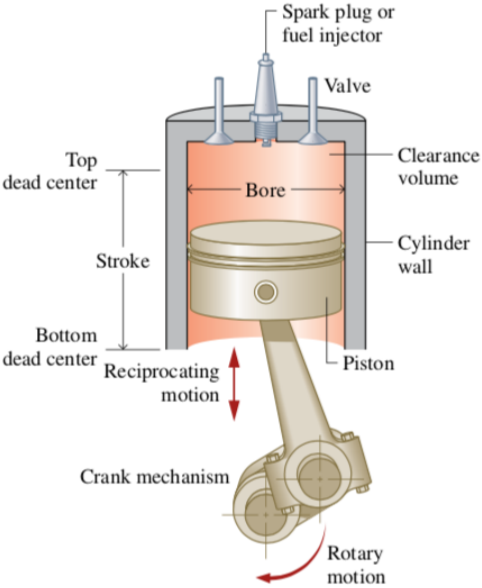
Cengel and Boles, *Thermodynamics: An Engineering Approach* (2019)



(*a*) Displacement volume

(*b*) Clearance volume

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



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

Engine metrics

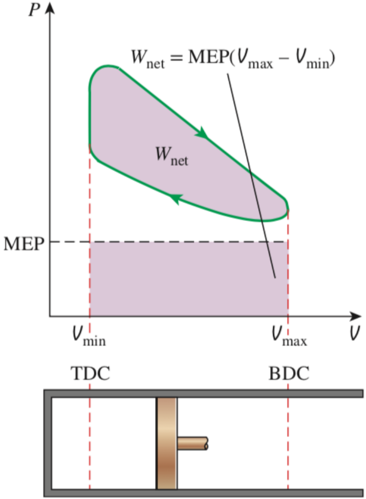
- the **compression ratio** is

$$r = \frac{\text{maximum volume}}{\text{minimum volume}} = \frac{V_{\text{BDC}}}{V_{\text{TDC}}}$$

- the **mean effective pressure** is

$$\text{MEP} = \frac{\text{net work over one cycle}}{\text{displacement volume}}$$

Mean effective pressure



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

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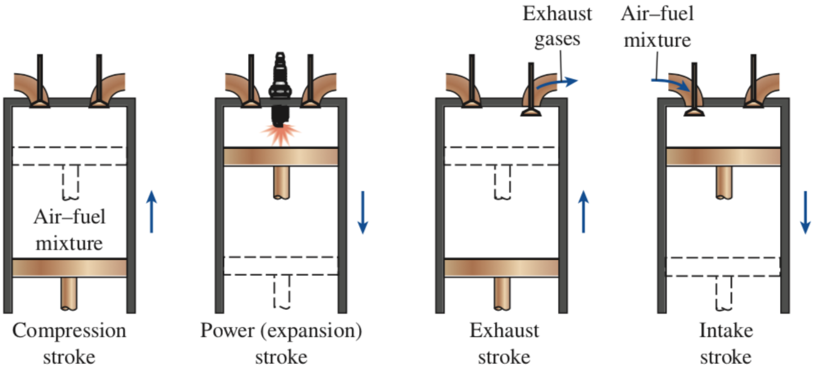
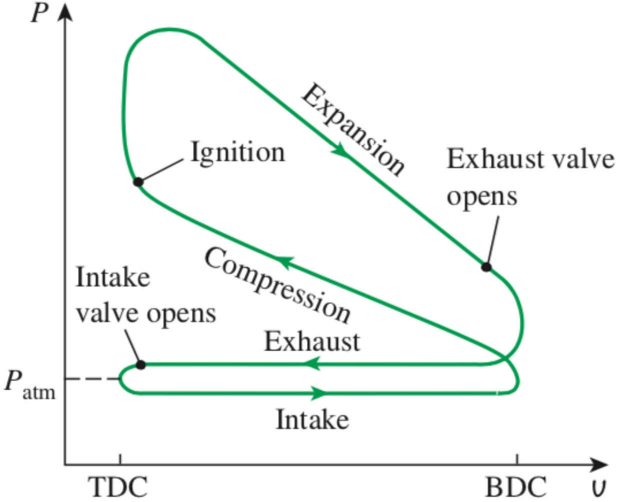
Processes (‘strokes’) in a four-stroke engine



Wikipedia animation

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

p-v diagram of a four-stroke engine cycle



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

Two-stroke engines

- two-stroke engines use only compression and power strokes
- compared to four-stroke engines, they typically have
    - higher power-to-weight ratios
    - lower efficiencies
- they're used in motorcycles, chainsaws, lawnmowers, . . .

Wikipedia animation

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This class greatly simplifies engine analysis

- internal combustion engines have all sorts of complexities
    - combustion chemistry
    - non-equilibrium states
    - work inputs to compress gases
    - heat transfer through cylinder walls
    - irreversibilities from temperature and pressure gradients
- to learn the basics, we make many simplifying assumptions
- in practice, real engine analyses use computer simulations

Simplifying assumptions

- we analyze engines under the **air-standard assumptions**:
    - ◇ the working fluid is a fixed mass of air behaving as an ideal gas
    - ◇ combustion is heat transfer from an external reservoir
    - ◇ there are no exhaust or intake processes
    - ◇ all processes are internally reversible
- we sometimes add the **cold** air-standard assumption:
    - ◇ specific heats are constant at their room-temperature values
- we also often assume that KE and PE effects are negligible

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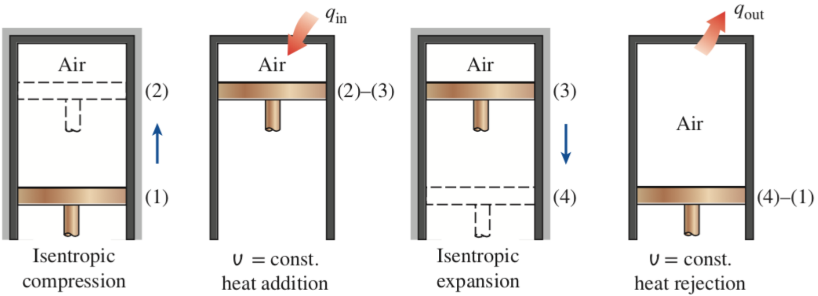
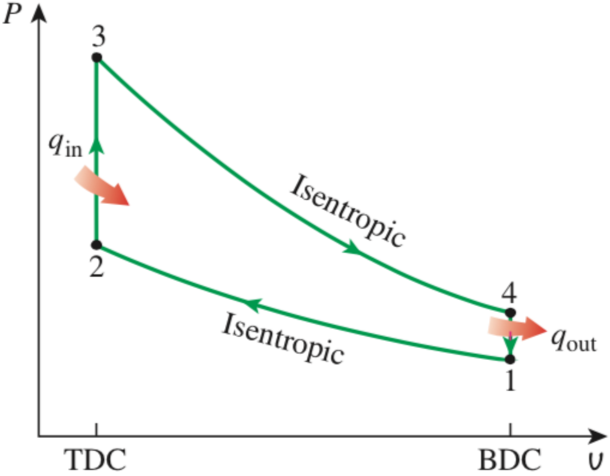
The air-standard Otto cycle models spark-ignition engines



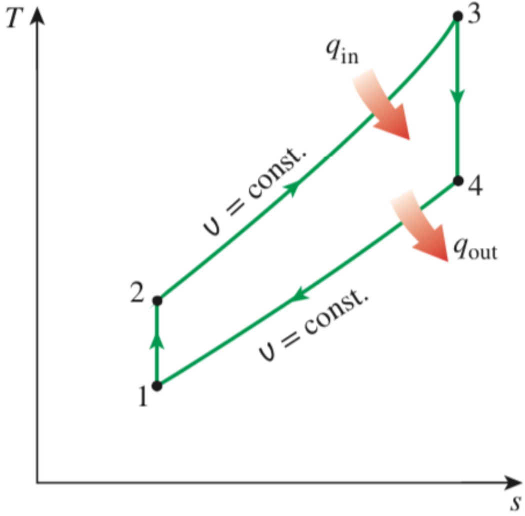
Cengel and Boles, *Thermodynamics: An Engineering Approach* (2019)

p-v diagram of the air-standard Otto cycle



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

T-s diagram of the air-standard Otto cycle



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

Air-standard Otto cycle energy balances

- under the air-standard assumptions, the system is closed
- if KE and PE effects are negligible, then in each process

$$\Delta U = m\Delta u = Q - W$$

- processes 1→2 and 3→4 are isentropic, so $Q_{12} = Q_{34} = 0$
- processes 2→3 and 4→1 are isochoric, so $W_{23} = W_{41} = 0$
- so energy balances on each process give
  - ◇ input (compression) work: $W_{12} = m(u_2 - u_1)$
  - ◇ input (combustion) heat transfer: $Q_{23} = m(u_3 - u_2)$
  - ◇ output (expansion) work: $W_{34} = m(u_3 - u_4)$
  - ◇ output (exhaust) heat transfer: $Q_{41} = m(u_4 - u_1)$

Air-standard Otto cycle efficiency

- the air-standard Otto cycle is a power cycle, so its efficiency is

$$
\begin{aligned}
\eta &= \frac{\text{net work output}}{\text{heat transfer input}} = \frac{W_{34} - W_{12}}{Q_{23}} \\
&= \frac{m(u_3 - u_4) - m(u_2 - u_1)}{m(u_3 - u_2)} \\
&= \frac{u_3 - u_2 - (u_4 - u_1)}{u_3 - u_2} \\
\implies \eta &= 1 - \frac{u_4 - u_1}{u_3 - u_2}
\end{aligned}
$$

Cold air-standard Otto cycle analysis

- 1→2 and 3→4 are isentropic, so if $k = c_p/c_v$ is constant, then

  $$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \text{ and } \frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{k-1}$$

  (see lecture 30, slides 9–13)
- but $V_1 = V_4,\ V_2 = V_3$, and $r = V_1/V_2$, so

  $$\frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(\frac{V_1}{V_2}\right)^{k-1} = r^{k-1}$$

Cold air-standard Otto cycle efficiency

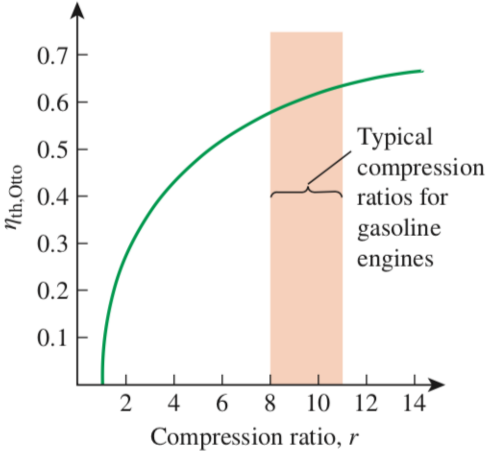
- $\Delta u = c_v \Delta T$ for an ideal gas with constant specific heats
- so in cold air-standard Otto cycle analysis,

$$\eta = 1 - \frac{u_4 - u_1}{u_3 - u_2} = 1 - \frac{\cancel{c_v}(T_4 - T_1)}{\cancel{c_v}(T_3 - T_2)} = 1 - \frac{T_1}{T_2}\left(\cancel{\frac{T_4/T_1 - 1}{T_3/T_2 - 1}}\right)$$

- the last term equals 1 since $T_4/T_1 = T_3/T_2$
- but $T_1/T_2 = 1/r^{k-1}$ in the cold air-standard Otto cycle, so

$$\eta = 1 - \frac{1}{r^{k-1}}$$

Otto cycle efficiency increases with compression ratio



- in practice, **knocking** puts an upper limit on compression ratio

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