Lecture 18

Topic 4

Power & Refrigeration Cycles

Topic

– 4.3 Otto Cycle

Reading:

Ch 10: 10.7 – 10.8 Borgnakke & Sonntag Ed. 8

Ch 9: 9-4 – 9-5 Cengel and Boles Ed. 7

4.0 Power and Refrigeration Cycles

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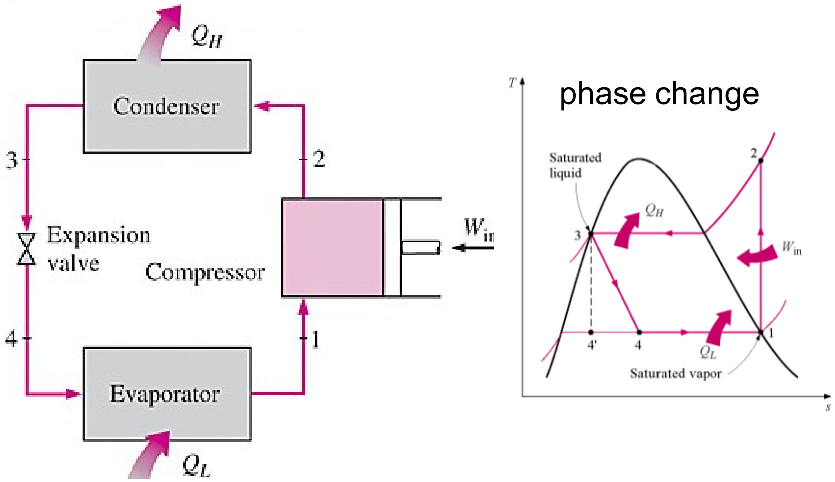
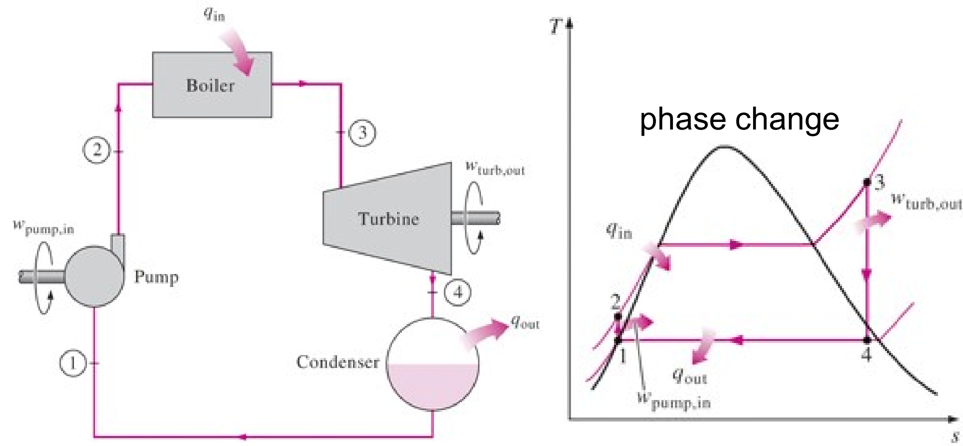
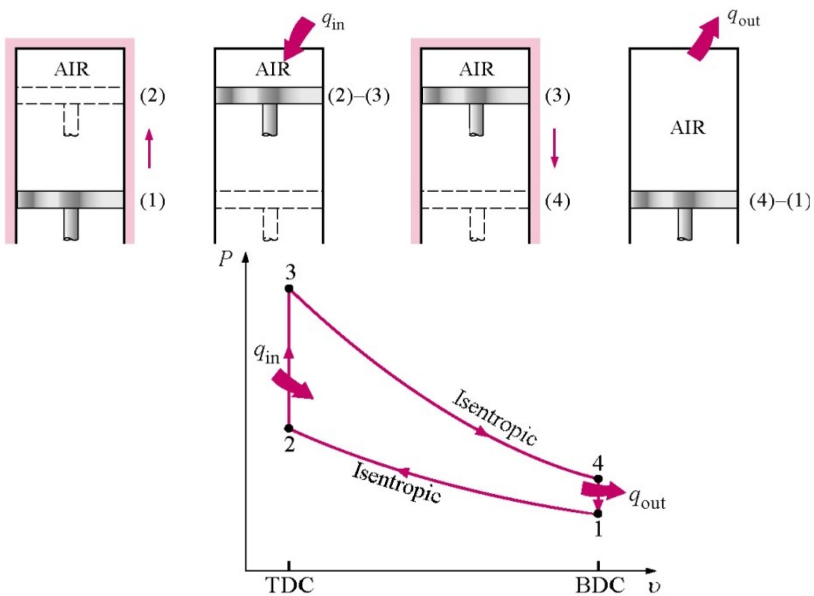
Refrigeration Cycle



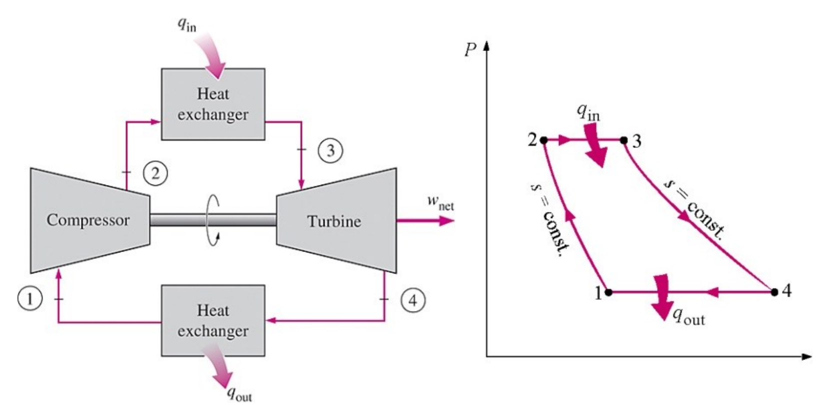
Rankine Cycle (power plant)



Otto/Diesel Cycle (IC engine)

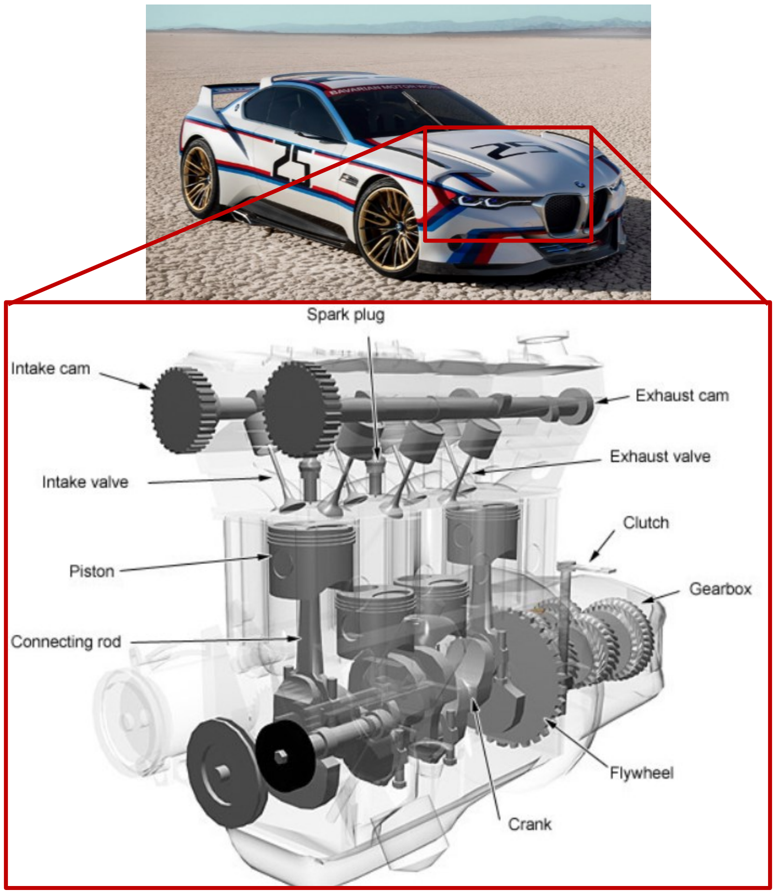


Brayton Cycle (gas turbine)



4.3 IC Engine … why?

IC engine



Electric vehicle

Comparing electric vehicle vs. IC engine

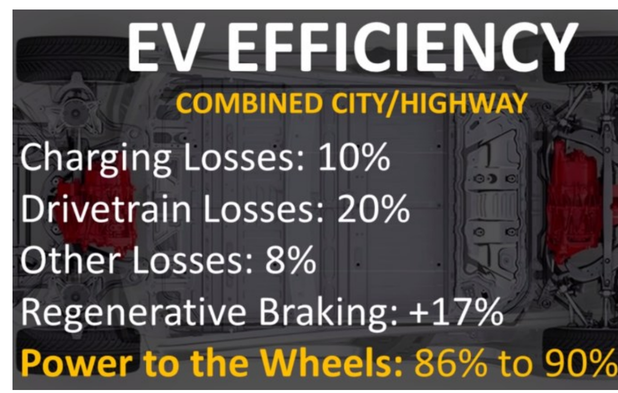
- Is there a “silver bullet”?
- Proper engineering analysis and critical thinking required

4.3 Critical analysis

https://insideevs.com/features/392202/ice-vs-ev-inefficient-combustion-engine/

Analysis based on efficiency

- Gasoline: ~79 times greater energy density
- Battery is more energy efficient
  - IC engine: chemical energy → heat → work
  - Battery: chemical energy → work
- Argument: battery – less energy per distance.
  - Evidence presented
- "… an electric vehicle charged on a dirty grid even power by coal will still be better for the environment than the average gas burning vehicle."
  - No evidence presented
- Other thermal impacts to consider
  - Low temperature stability/reliability
  - Passenger heating



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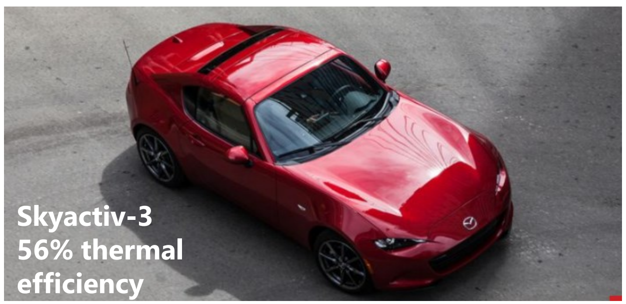
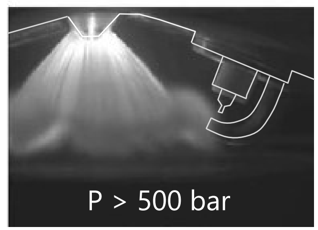
4.3 Research into cleaner fuels

- Research into batteries & cleaner fuel-powered engines
- Future ICE and hybrid technology

Mazda Says Its Next-Generation Gasoline Engine Will Run Cleaner Than an Electric Car





roadandtrack.com

1 https://www.theverge.com/2017/8/8/16099536/mazda-compression-ignition-engine-technology
2 https://www.roadandtrack.com/new-cars/car-technology/a15912314/mazda-skyactiv-3-gas-clean-as-ev/

MATERIALS FOR ENERGY | FEATURE

Beyond the lithium-ion battery

31 Oct 2018

This article first appeared in the 2018 *Physics World Focus on Energy Technologies*

Engineering a sustainable, electrified future means developing battery materials with properties that surpass those found in current technologies, as Jan Provoost explains

3 https://physicsworld.com/a/beyond-the-lithium-ion-battery/

4.3 Otto & Diesel Cycles

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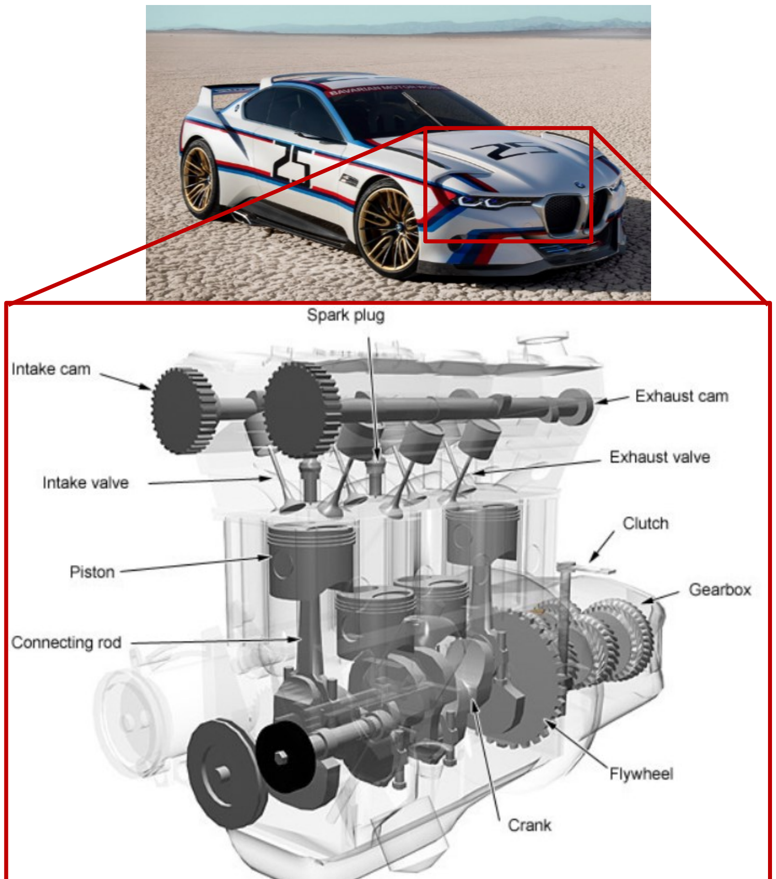
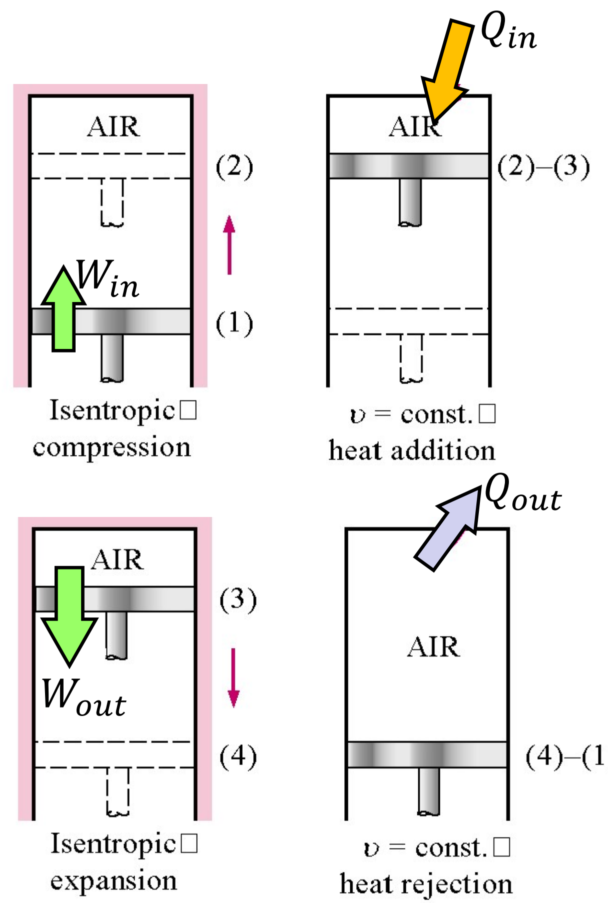
Otto/Diesel Cycle – transfer heat to useful work out (e.g. move vehicle).

- Cycle contained entirely within a piston/cylinder device
- Otto Cycle → air standard cycle for spark-ignition engine



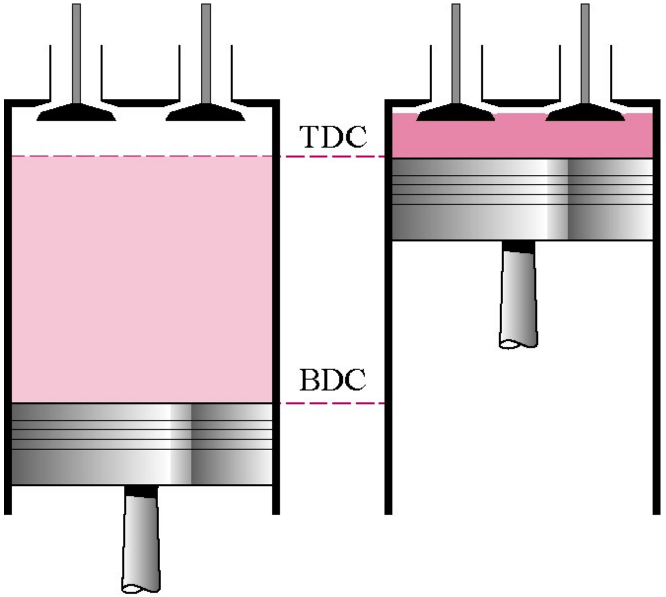


https://www.youtube.com/watch?v=DKF5dKo_r_Y

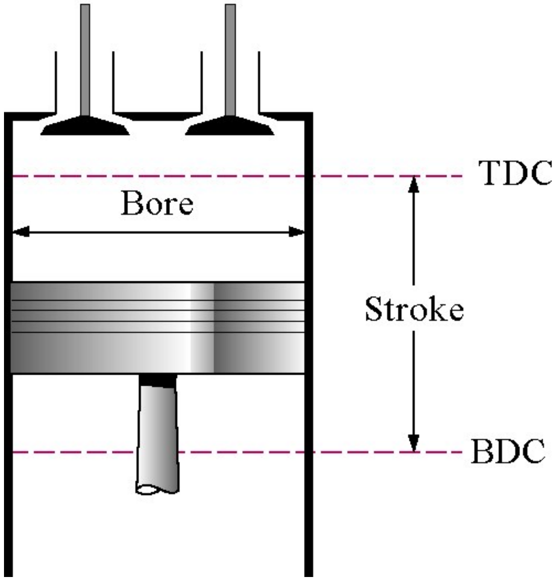
4.3 Terminology for Reciprocating Devices

- Top dead centre (TDC): piston's highest position
- Bottom dead centre (BDC): piston's lowest position
- Displacement volume: $V_D = BDC_{volume} - TDC_{volume}$ (volume swept by piston)
- Bore: diameter of cylinder
- Stroke: distance piston moves up/down

$$V_D = \frac{\pi}{4} bore^2 (stroke)$$



(a) Displacement volume   (b) Clearance volume



4.3 Terminology for Reciprocating Devices

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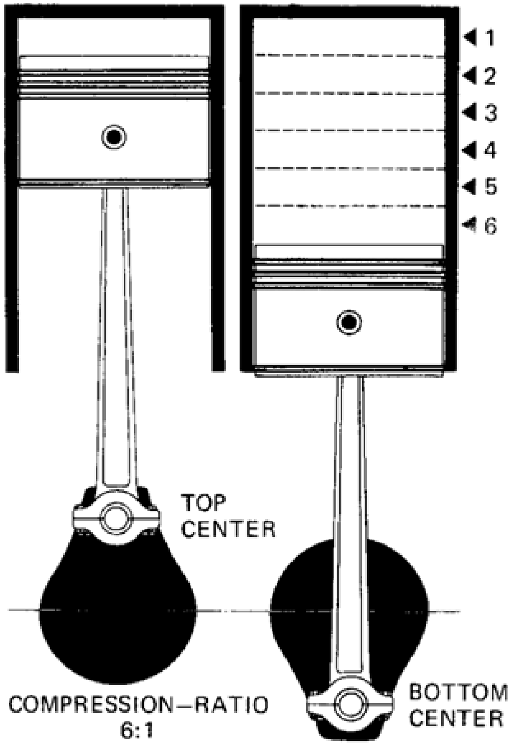
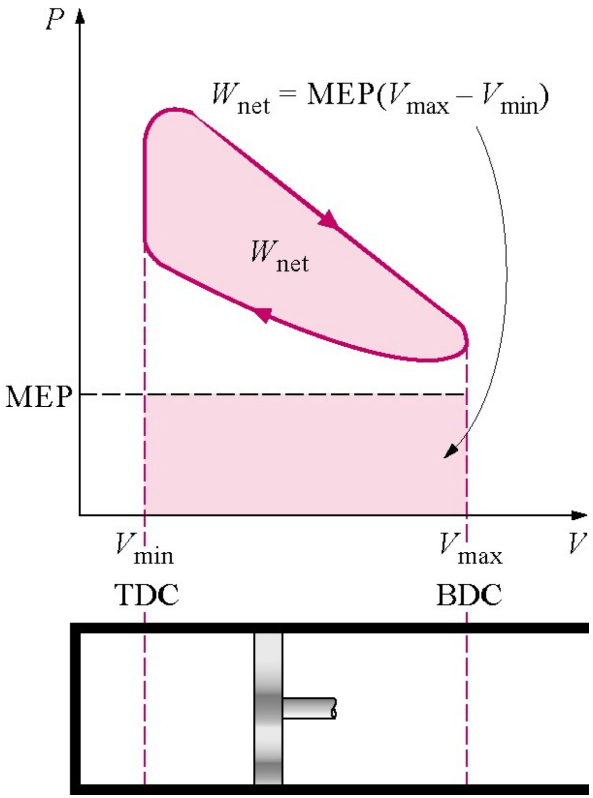
Compression ratio (r): ratio of the maximum volume to the minimum cylinder volume.

$$r = \frac{V\max}{V\min} = \frac{V_{BDC}}{V_{TDC}}$$



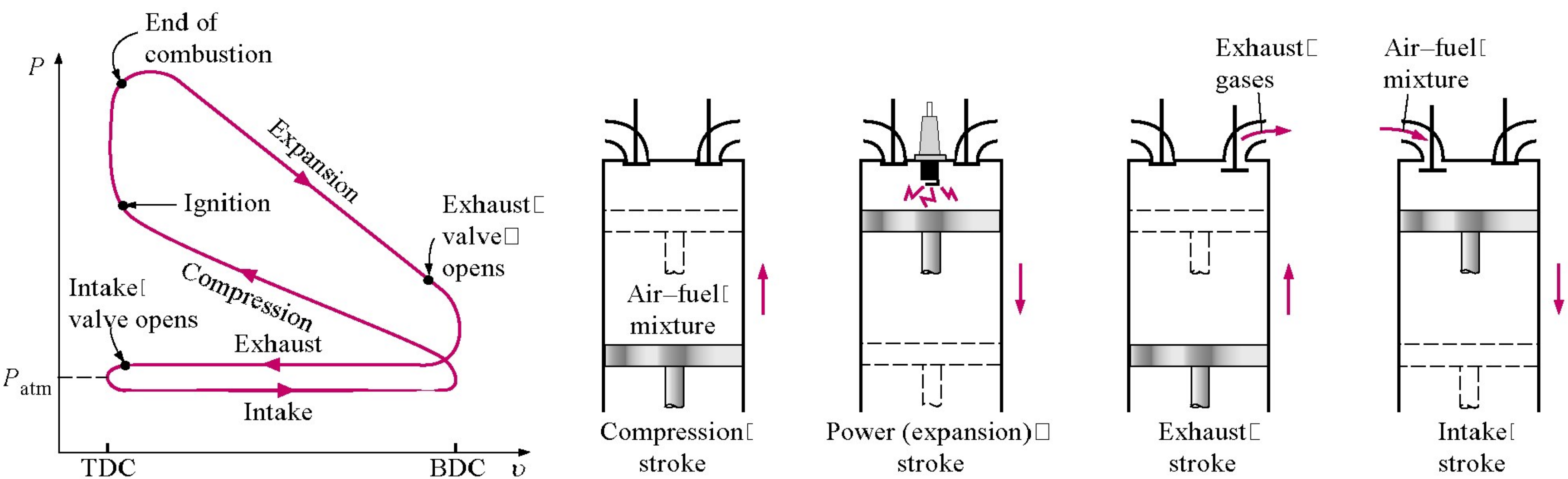
Mean effective pressure (MEP): fictitious pressure that, if it operated on the piston during the entire power stroke, would produce the same amount of net work as that produced during the real cycle.

$$MEP = \frac{W_{net}}{V_{\max} - V_{\min}} = \frac{w_{net}}{v_{\max} - v_{\min}}$$



4.3 Otto Cycle

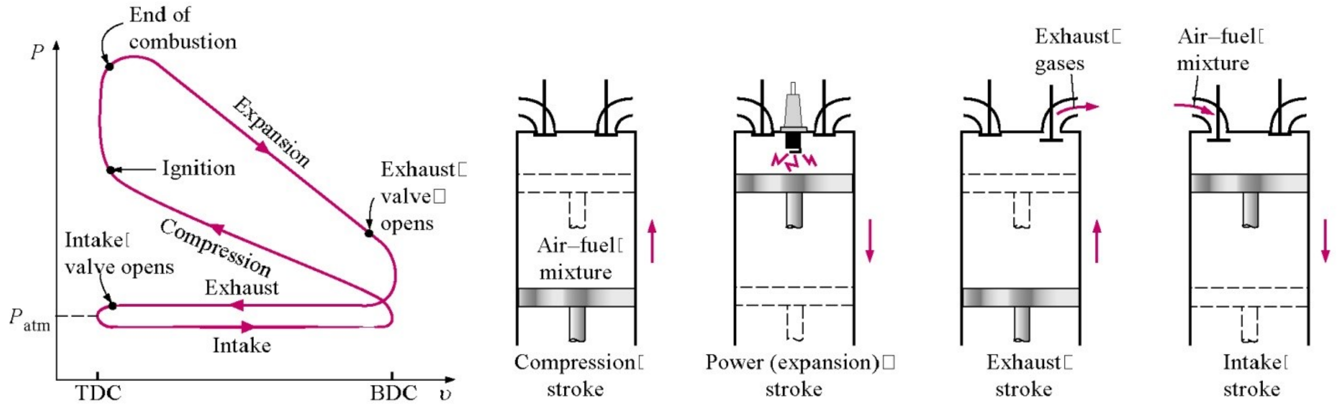
- Four-stroke engine: piston executes four complete strokes
  - Compression stroke: piston compresses gas to high P,T
  - Power (expansion) stroke: piston pushed downwards by high pressure
  - Exhaust stroke: piston moves upwards and outgases exhaust
  - Intake stroke: piston moves downwards to draw in new fuel and air mixture



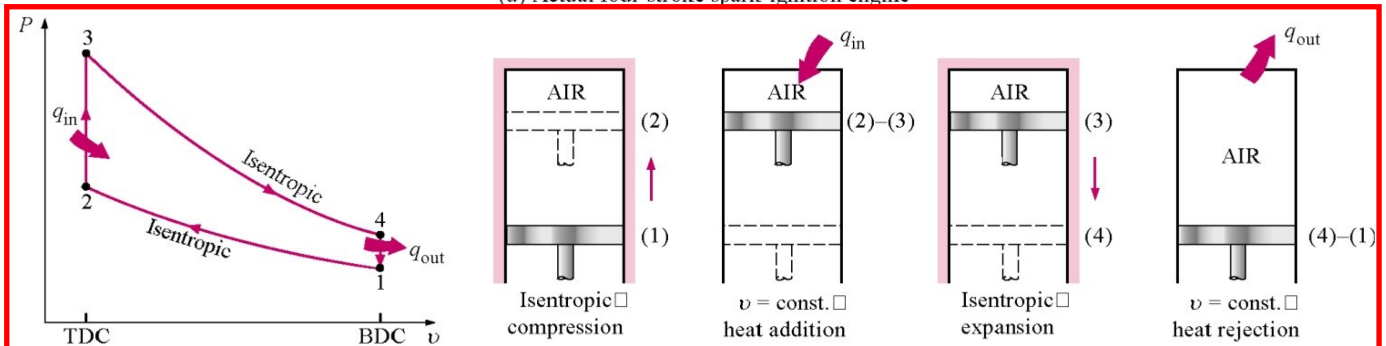
(a) Actual four-stroke spark-ignition engine

4.3 Otto Cycle – Simplifying Analysis

- Otto cycle made simple(r)
  - Closed cycle (no valves)
  - Woking fluid is air
  - Combustion is modelled as heat addition at TDC
  - Exhaust modelled as heat loss to surroundings
  - Intake is not modelled



(a) Actual four-stroke spark-ignition engine

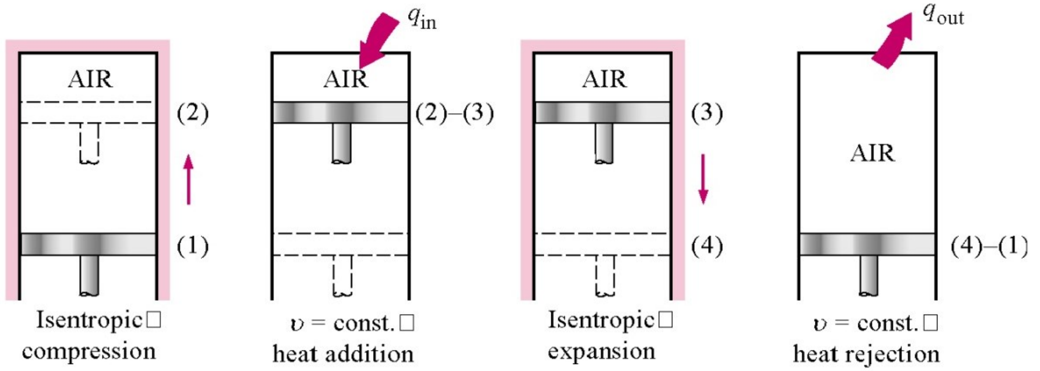


(b) Ideal Otto cycle

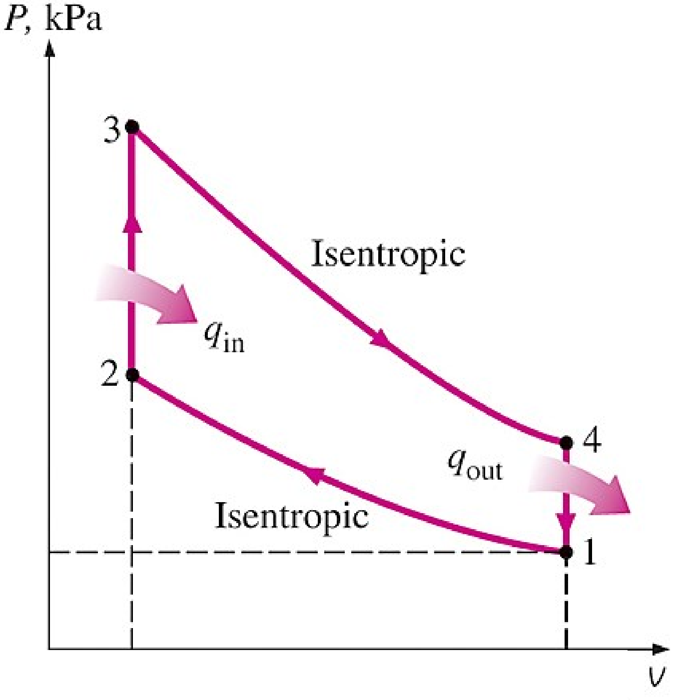
4.3 Otto Cycle – Simplifying Analysis

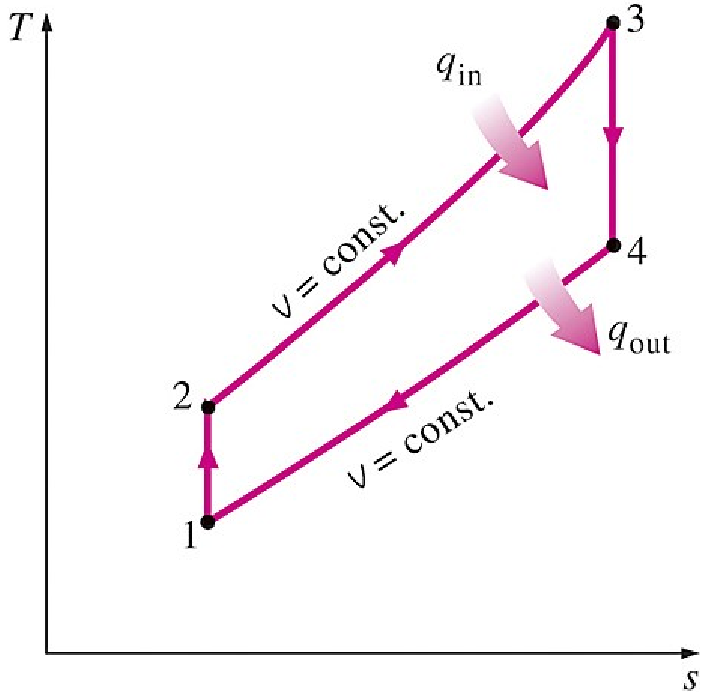
- Ideal Otto Cycle

Process	**Description**
1-2	Isentropic compression
2-3	Constant volume heat addition
3-4	Isentropic expansion
4-1	Constant volume heat rejection



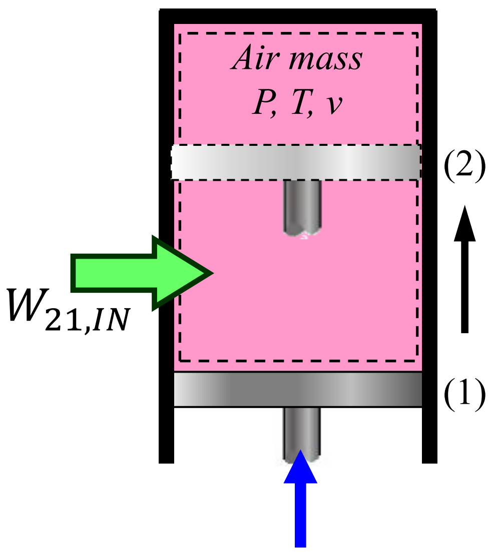
(*b*) Ideal Otto cycle

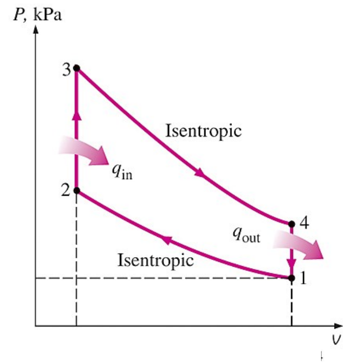




4.3 Ideal Otto Cycle

- Air is treated as an <u>ideal gas</u>





Process 1-2: isentropic compression

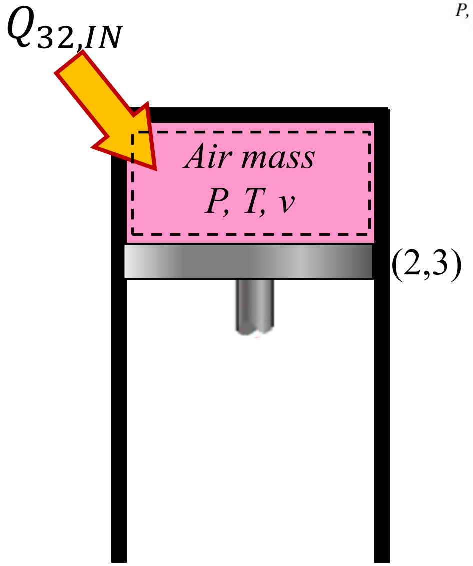
- Ideal: Adiabatic, reversible ($s_2 = s_1$)
- 1[st] Law: $\Delta U = Q - W$
  - $W_{21,IN} = m(u_2 - u_1)$
  - $W_{21,IN} = mC_V(T_2 - T_1)$
- 2[nd] Law analysis
  - $s_2 - s_1 = \int \frac{\delta q}{T} + s_{gen} \rightarrow s_2 - s_1 = 0$
  - Ideal gas: (lecture 12)
    - $s_2 - s_1 = \int_1^2 C_V \frac{dT}{T} + Rln\left(\frac{v_2}{v_1}\right)$ OR $s_2 - s_1 = \int_1^2 C_P \frac{dT}{T} - Rln\left(\frac{P_2}{P_1}\right)$
  - If constant specific heat, T, P, v relationship
    - $C_V ln\left(\frac{T_2}{T_1}\right) = Rln\left(\frac{v_1}{v_2}\right) \rightarrow \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$
    - $C_P ln\left(\frac{T_2}{T_1}\right) = Rln\left(\frac{P_2}{P_1}\right) \rightarrow \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{k-1/k}$
  - If variable specific heat, T, P, v relationship
    - $s^o_{T2} = s^o_{T1} + Rln\left(\frac{P_2}{P_1}\right)$
- Isentropic relations: $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(n-1)/n} = \left(\frac{V_1}{V_2}\right)^{n-1}$ & $\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^n$

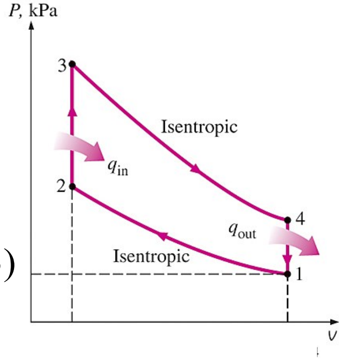
4.3 Ideal Otto Cycle

- Air is treated as an ideal gas

Process 2-3: constant volume heat addition

- Heat addition → $P_3 > P_2$, $T_3 > T_2$.
- 1st Law: $\Delta U = Q - W$
  - $Q_{32,IN} = m(u_3 - u_2)$
  - $Q_{32,IN} = mC_V(T_3 - T_2)$



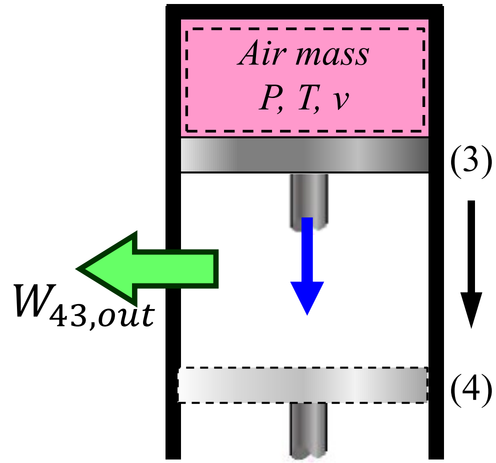


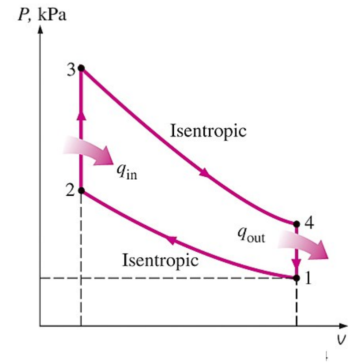
4.3 Ideal Otto Cycle

- Air is treated as an ideal gas

Process 3-4: isentropic expansion

- Adiabatic, reversible ($s_4 = s_3$)
- 1st Law: $\Delta U = Q - W$
  - $W_{43,out} = m(u_3 - u_4)$
  - $W_{43,out} = mC_V(T_3 - T_4)$





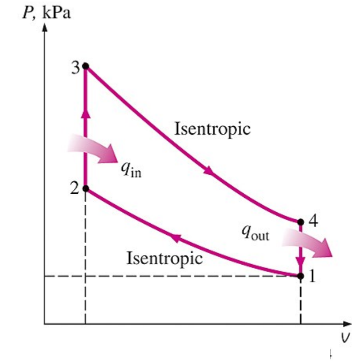
- 2nd Law analysis
  - $s_4 - s_2 = \int \frac{\delta q}{T} + s_{gen} \rightarrow s_4 - s_3 = 0$
  - Ideal gas: (lecture 12)
    - $s_4 - s_3 = \int_3^4 C_V \frac{dT}{T} + Rln\left(\frac{v_4}{v_3}\right)\ OR\ \ s_4 - s_3 = \int_3^4 C_P \frac{dT}{T} - Rln\left(\frac{P_4}{P_3}\right)$
  - If constant specific heat, T, P, v relationship
    - $C_V ln\left(\frac{T_4}{T_3}\right) = Rln\left(\frac{v_3}{v_4}\right) \rightarrow \frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{k-1}$
    - $C_P ln\left(\frac{T_4}{T_3}\right) = Rln\left(\frac{P_4}{P_3}\right) \rightarrow \frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{k-1/k}$
  - If variable specific heat, T, P, v relationship
    - $s^o_{T4} = s^o_{T2} + Rln\left(\frac{P_4}{P_3}\right)$

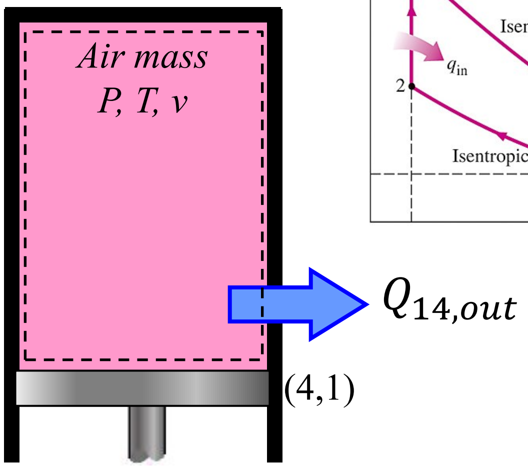
4.3 Ideal Otto Cycle

- Air is treated as an ideal gas

Process 4-1: constant volume heat rejection

- Heat addition → $P_1 < P_4$, $T_1 > T_4$
- 1st Law: $\Delta U = Q - W$
  - $Q_{14,out} = m(u_4 - u_1)$
  - $Q_{14,out} = mC_V(T_4 - T_1)$

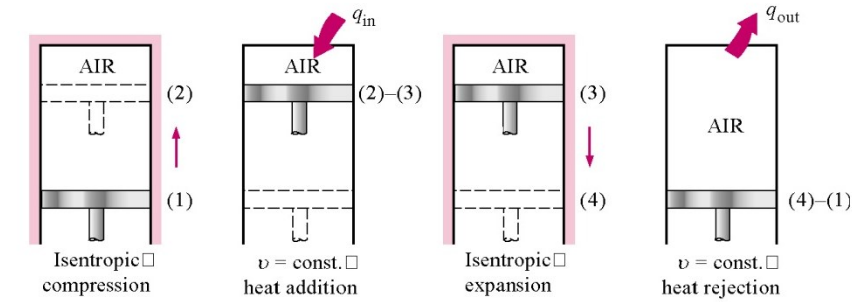




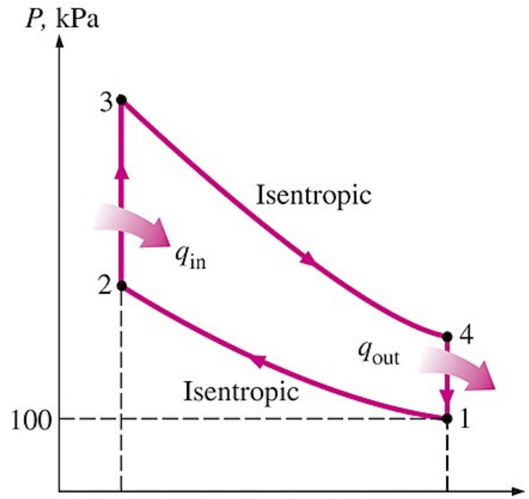
4.3 Otto Cycle – Example

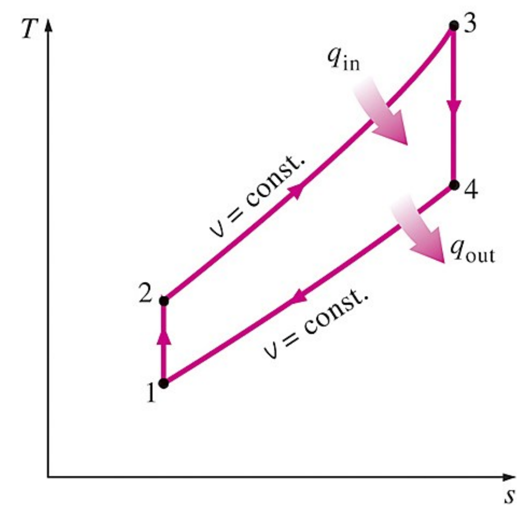
Example 4-5: An Otto cycle operates with a compression ratio (r) of 9. At the beginning of the compression stroke the pressure is 100 kPa, 15°C. The maximum pressure achieved is 6000 kPa. Assuming an *ideal* Otto cycle, with m = 1 kg air as the working fluid and constant specific heats, determine:

a) The heat from combustion (Q_{in} or Q_{23})
b) The maximum temperature
c) The heat rejected
d) The net thermal efficiency and IMEP



(b) Ideal Otto cycle





Air properties: R = 0.287 kJ/kgK, C_V = 0.717kJ/kgK, k = 1.4

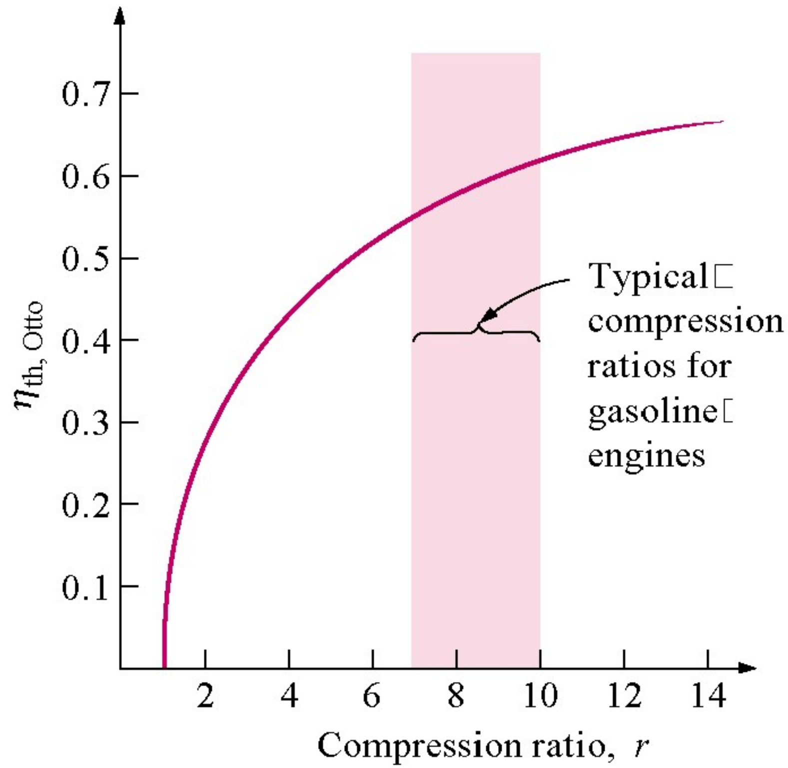
4.3 Otto Cycle – Thermal Efficiency

Compression ratio

- Otto cycle efficiency expressed as a function of compression ratio:

$$\boxed{\eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}}}$$

$r = V_1/V_2$ (i.e. compression ratio)



4.3 Otto Cycle – Thermal Efficiency

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- Otto cycle thermal efficiency can be expressed as a function of compression ratio

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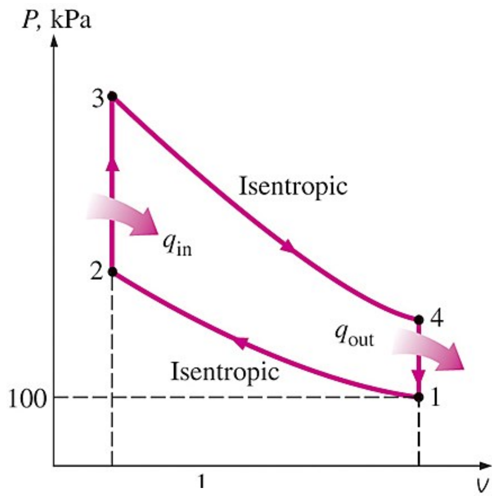


- $\eta_{th,Otto} = \frac{W_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$
- $\eta_{th,Otto} = 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)}$
- $\eta_{th,Otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$

- Processes 1-2 and 3-4 are isentropic $\rightarrow$ $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$ and $\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{k-1}$

- Since $V_3 = V_2$ and $V_4 = V_1$ $\rightarrow$ $\frac{T_2}{T_1} = \frac{T_3}{T_4}$ and $\frac{T_4}{T_1} = \frac{T_3}{T_2}$

- Otto cycle efficiency: $\eta_{th,Otto} = 1 - \frac{T_1}{T_2}$ $\qquad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} = (r)^{k-1}$

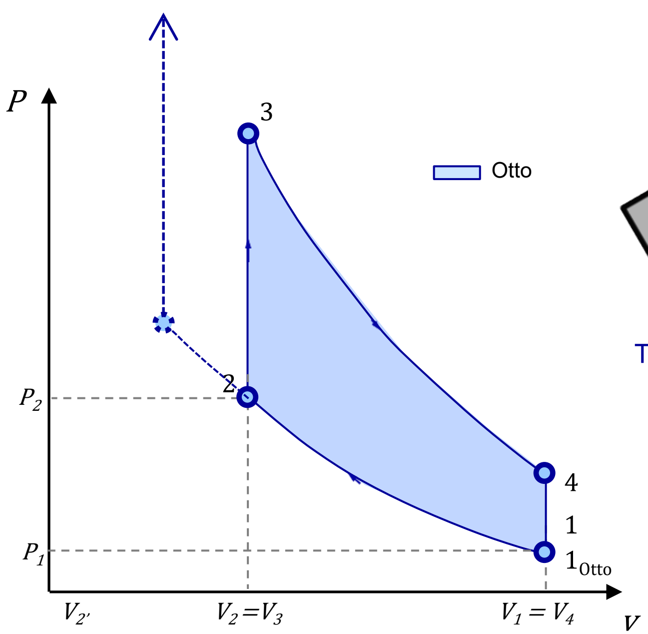
$$\eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}}$$

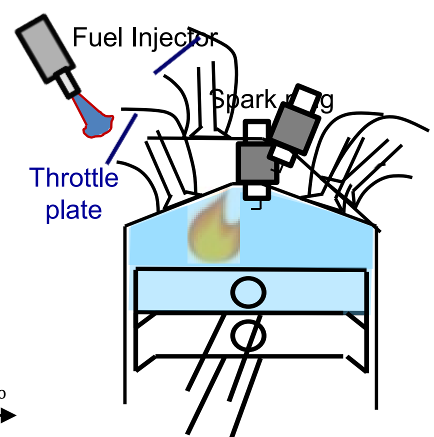
4.3 Otto Cycle – Thermal Efficiency

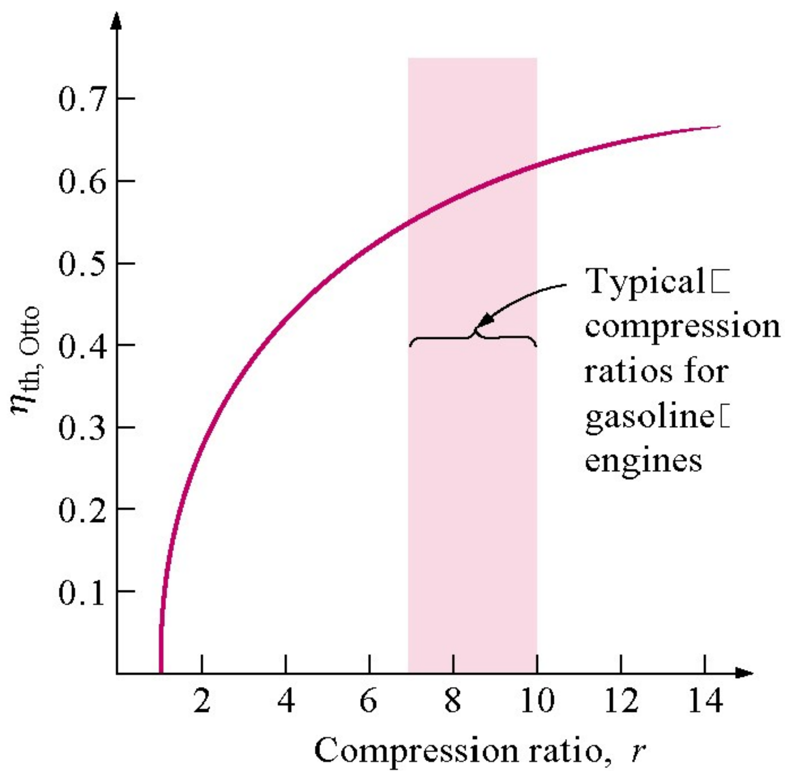
Compression ratio

$$\eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}}$$

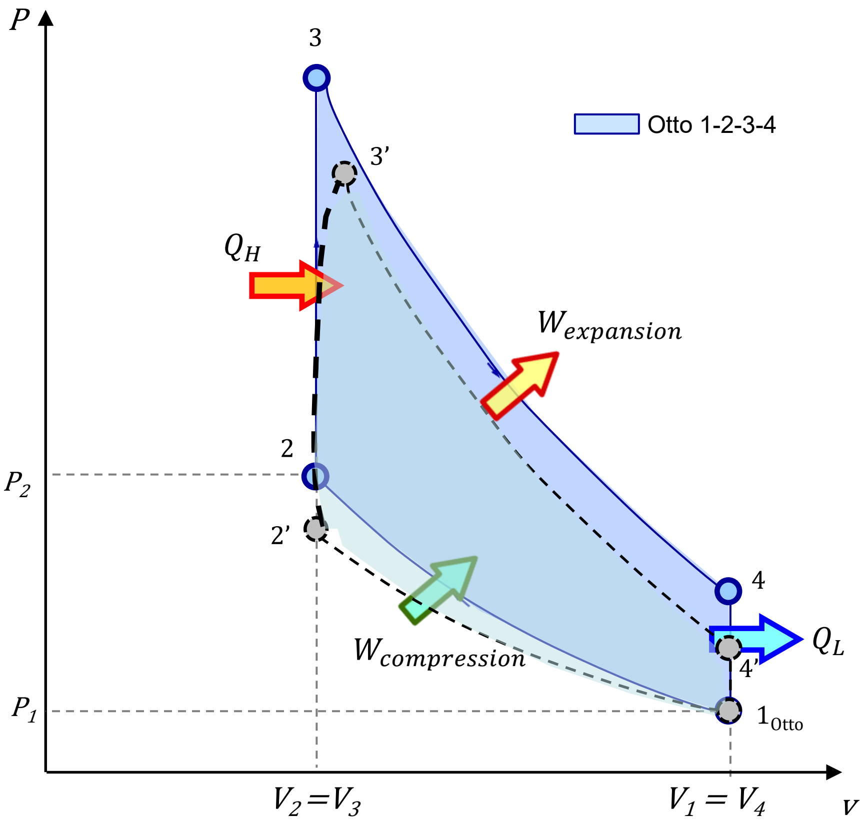
- Higher compression ratio (r) → higher thermal efficiency (k=1.4)
- The limit on r depends on the fuel. High temperatures will cause fuel to prematurely ignite (i.e. unwanted auto-ignition).







4.3 Otto Cycle – Ideal vs. Reality



- Compression
  - Not adiabatic nor reversible
- Constant volume heat addition
  - Combustion is not instantaneous
  - Combustion efficiency ≠ 100%
- Expansion
  - Not adiabatic nor reversible
- Constant volume heat rejection
  - Open cycle analysis needed

- $\eta_{Ideal} = 0.55;\ \eta_{Reality} = 0.35 - 0.45$

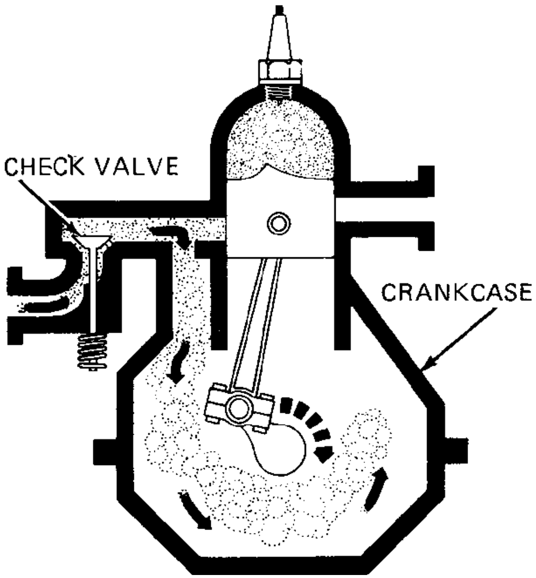
4.0 IC Engine – Extra – two-stroke engine

Two-stroke engines

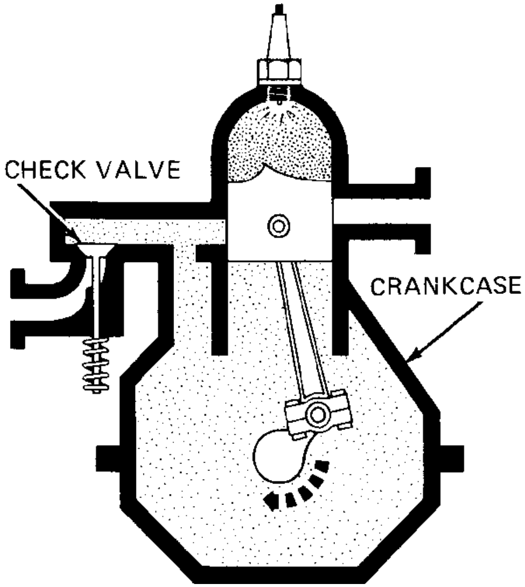
In two-stroke engines all four functions described in the 4-stroke cycle are executed in just 2 strokes: 1) the power stroke and 2) the compression stroke.

In these engines the crankcase is sealed and the outward motion of the piston is used to slightly pressurise the air-fuel mixture in the crankcase. Also the intake and exhaust valves are replaced by openings in the lower portion of the cylinder wall.

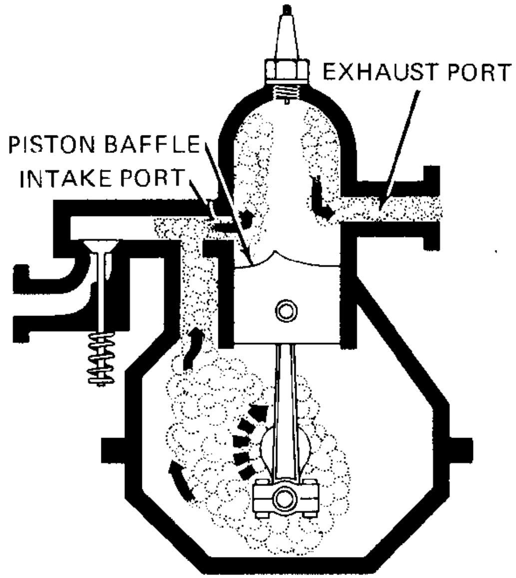
During the latter part of the power stroke, the piston uncovers first the exhaust port, allowing the exhaust gases to be partially expelled, and then the intake port, allowing the fresh air-fuel mixture to rush in and drive most of the remaining gases out of the cylinder. This mixture is then compressed as the piston moves upward during the compression stroke and is subsequently ignited by a spark plug.



A. Crankcase intake/
Cylinder Compression



B. Ignition/ Power/
Crankcase pressure



C. Cylinder Intake/
Cylinder Exhaust