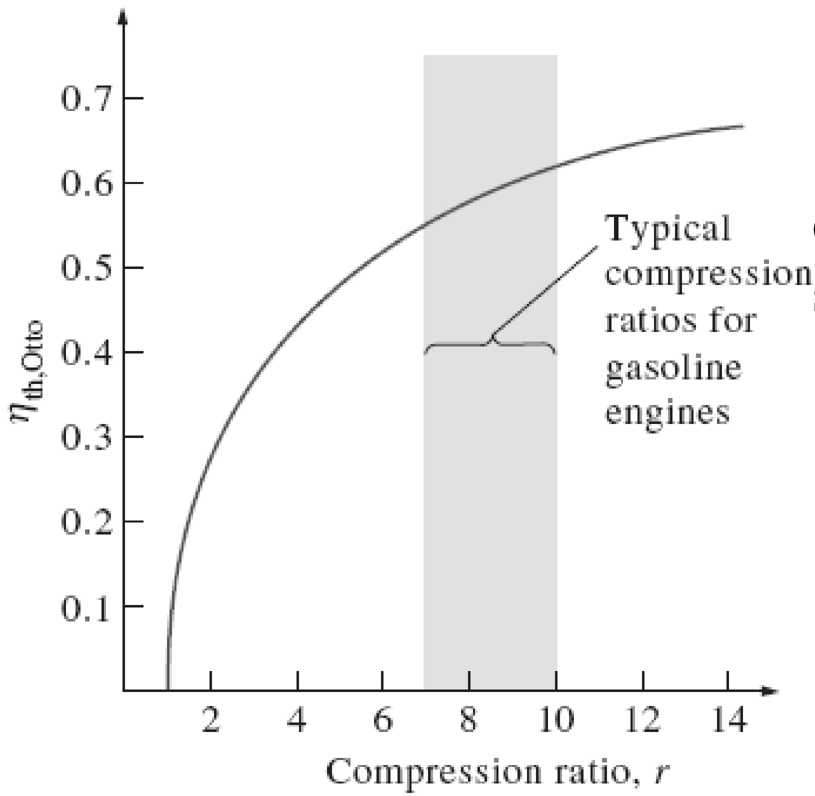
- Recap: Lecture 11th March 2014: 0830-0930 Hrs
  - Gas power cycles
  - Carnot cycle and its significance
  - Air standard assumptions
  - Overview of reciprocating engines
  - SI and CI engines
  - Otto cycle
  - Thermodynamic cycle
  - Efficiency of Otto cycle
  - 4-stroke engines



Thermal efficiency of the ideal Otto cycle as a function of compression ratio ($k = 1.4$).

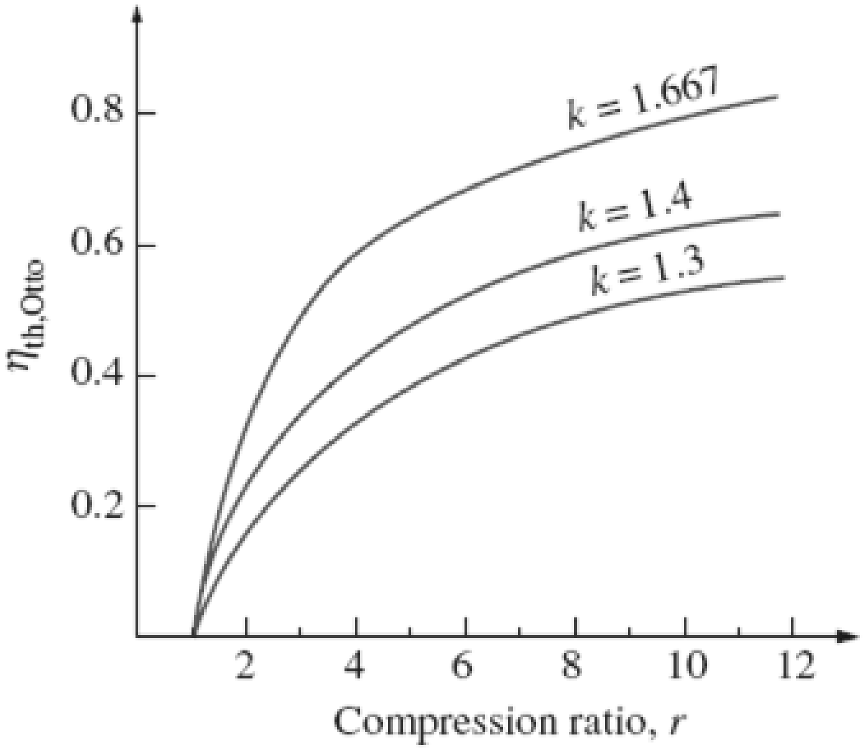
High compression: the temperature of the air–fuel mixture rises above the auto-ignition temperature of the fuel

Causes an early and rapid burn of the fuel at some point or points ahead of the flame front

This premature ignition of the fuel, called **autoignition**, produces an audible noise, which is called **engine knock.**

Tetraethyl lead had been added to gasoline because it is an inexpensive method of raising the *octane rating, which is a measure of the* engine knock resistance of a fuel.

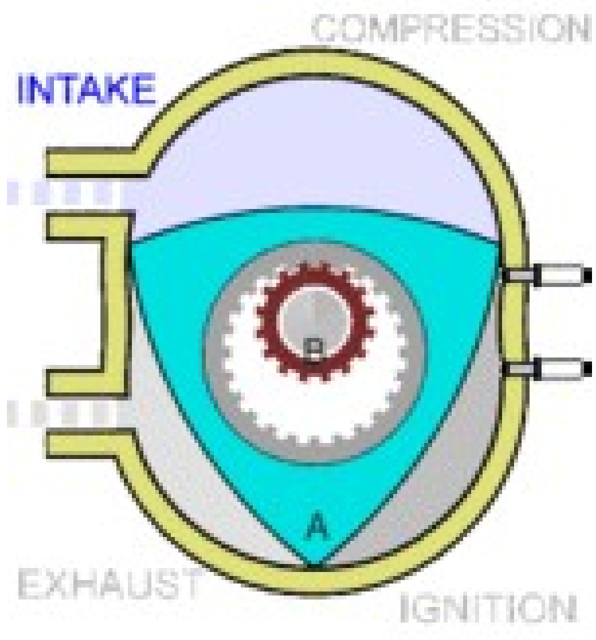
Leaded gasoline: releases toxic pollutants
Unleaded gasoline/petrol with high octane rating



The thermal efficiency of the Otto cycle increases with the specific heat ratio *k* of the working fluid.

- Efficiency also depends upon the ratio of specific heats
- For air, γ=1.4
- At higher temperatures, it decreases

- Rotary version of the Otto cycle: Wankel engine.
- Operates in 4-S type mode, but does not have piston-cylinder arrangement.



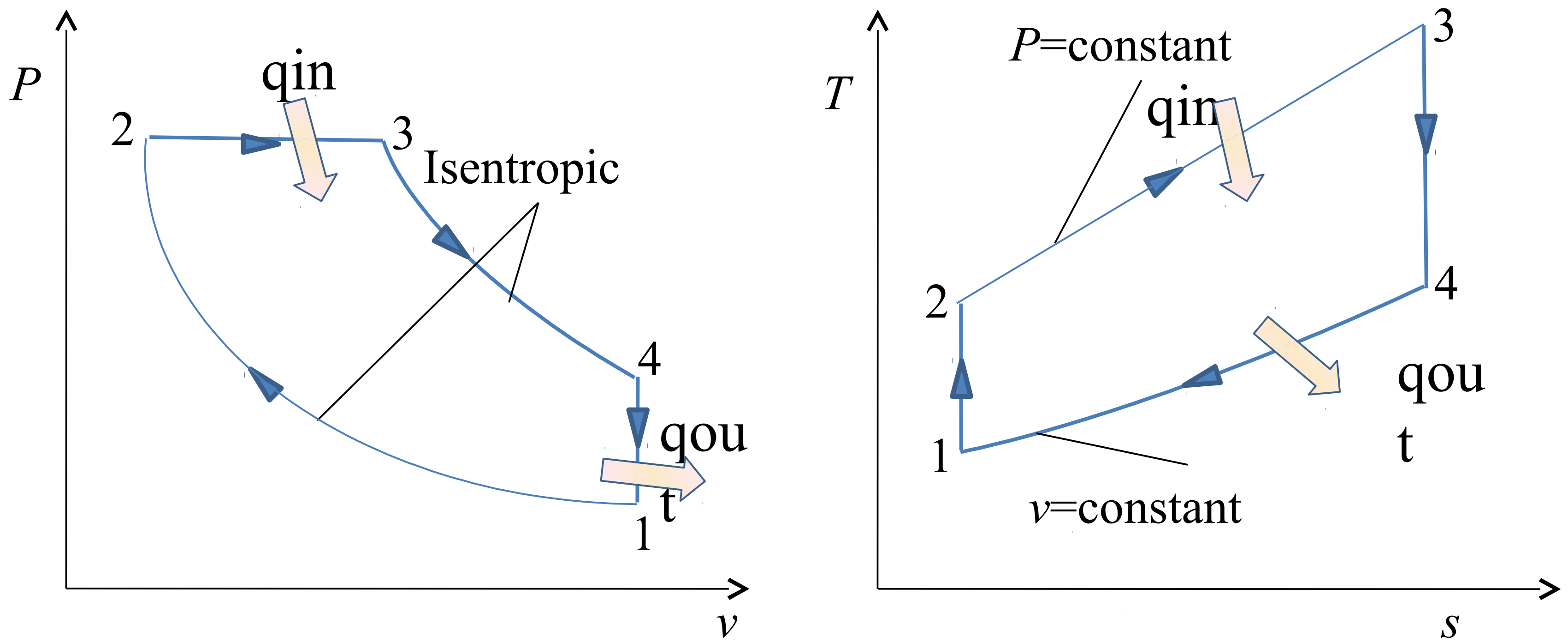
Diesel cycle

- The Diesel cycle is the ideal cycle for CI reciprocating engines proposed by Rudolph Diesel in the 1890s.
- In SI, the air–fuel mixture is compressed to a temperature that is below the autoignition temperature of the fuel, and the combustion process is initiated by firing a spark plug.
- In CI engines, the air is compressed to a temperature that is above the autoignition temperature of the fuel, and combustion starts on contact as the fuel is injected into this hot air.

Diesel cycle

- Diesel cycle consists of four processes:
  - Isentropic compression (1-2)
  - Isobaric (constant pressure) heat addition (2-3)
  - Isentropic expansion (3-4)
  - Isochoric (constant volume) heat rejection (4-1)
- All the processes are internally reversible.
- Thermodynamically the Otto and Diesel cycles differ only in the second process (2-3).
- For Otto cycle, 2-3: constant volume and for Diesel cycle, 2-3: constant pressure.

Diesel cycle



Ideal Diesel cycle on *P-v* and *T-s* diagrams

Diesel cycle

- Applying energy balance and assuming KE and PE to be zero:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta u$$

The heat transfer to and from the working fluid can be written as :

$$q_{in} = P_2(v_3 - v_2) + (u_3 - u_2) = h_3 - h_2 = c_p(T_3 - T_2)$$

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

Diesel cycle

- The thermal efficiency of the ideal Diesel cycle under the cold air standard assumptions becomes:

$$\eta_{th,Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{\gamma(T_3 - T_2)}$$

$$= 1 - \frac{T_1(T_4 / T_1 - 1)}{\gamma T_2(T_3 / T_2 - 1)}$$

- The cutoff ratio *rc*, as the ratio of the cylinder volumes after and before the combustion process: *rc =v3/v2*

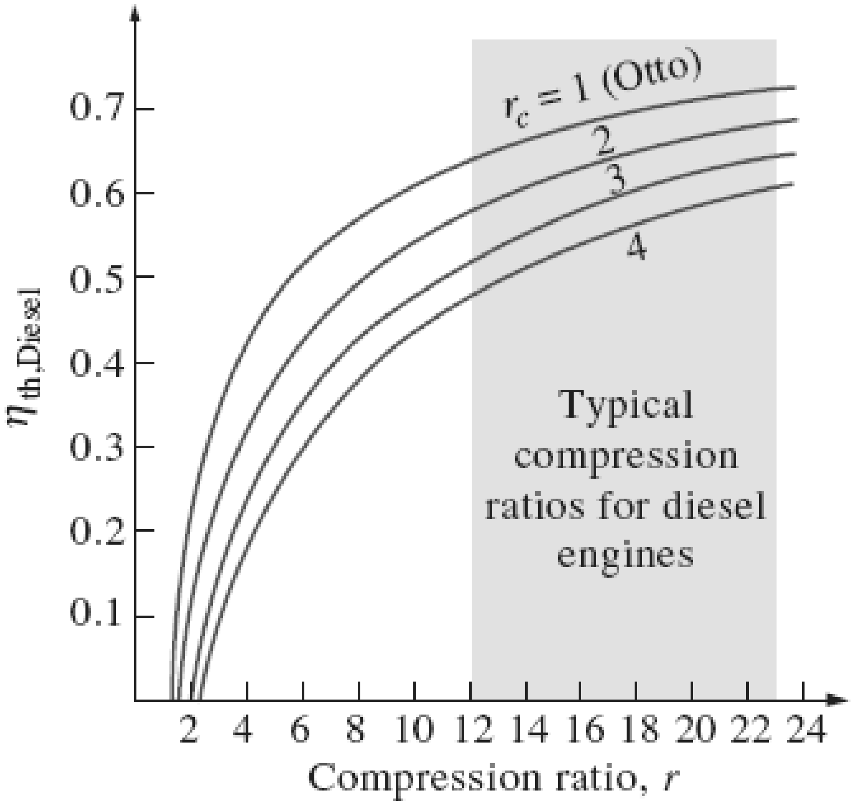
Diesel cycle

- Substituting these equations into the thermal efficiency relation and simplifying:

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}\right]$$

Where, r, is the compression ratio $= \frac{V_{\max}}{V_{\min}}$

- The quantity in the brackets is always >0 and therefore $\eta th,Diesel < \eta th,Otto$ for the same compression ratios.



Thermal efficiency of the ideal Diesel cycle as a function of compression and cutoff ratios ($k = 1.4$).

For same compression ratio, efficiency of diesel < efficiency of Otto

Usually diesel engines operate at much higher compression ratios and are therefore more efficient.

The diesel engines also burn the fuel more completely since they usually operate at lower revolutions per minute and the air–fuel mass ratio is much higher than spark-ignition engines

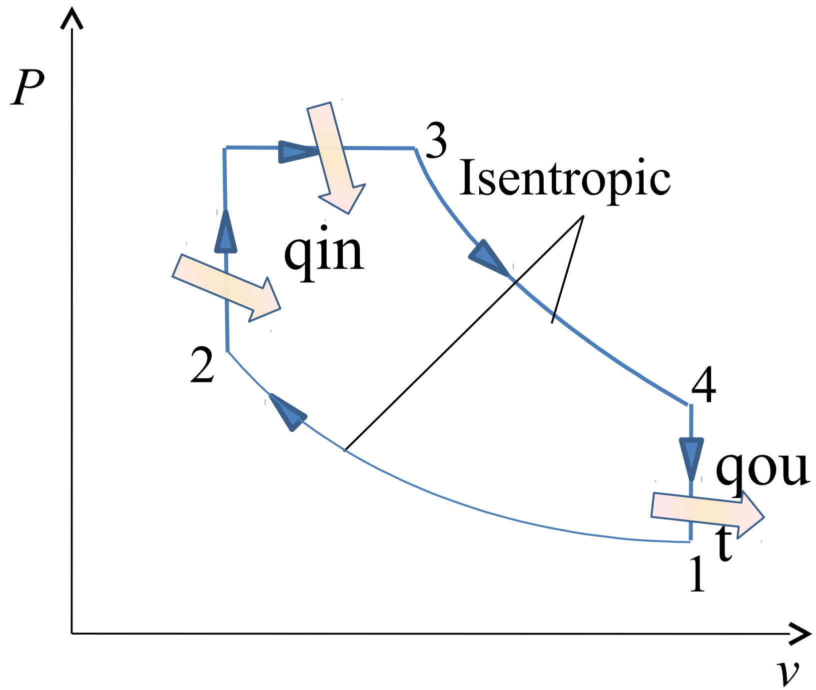
Hence used in locomotive engines, emergency power generation units, large ships, heavy trucks, buses, cars etc.

Engine is bulkier and has more vibrations, SI engines preferred in automobiles

Dual cycle

- Approximating heat addition by a constant pressure or constant volume process is too simplistic.
- Modelling the heat addition process by a combination of constant pressure and constant volume processes: dual cycle.
- The relative amounts of heat added during the two processes can be appropriately adjusted.
- Both Otto and Diesel cycle can be obtained as a special case of the dual cycle.

Dual cycle



Ideal dual cycle on *P-v* diagram

What will this cycle look like on T-s diagram?

What is the thermal efficiency of such a cycle?

Thermal Efficiency is given as

$$\eta_{th} = 1 - \frac{T_1\, r_p\, r_c^{\gamma} - T_1}{\left\{\left(T_1\, r^{\gamma - 1}\, r_p - T_1\, r^{\gamma - 1}\right) + \gamma\left(T_1\, r^{\gamma - 1}\, r_p\, r_c - T_1\, r^{\gamma - 1}\, r_p\right)\right\}}$$

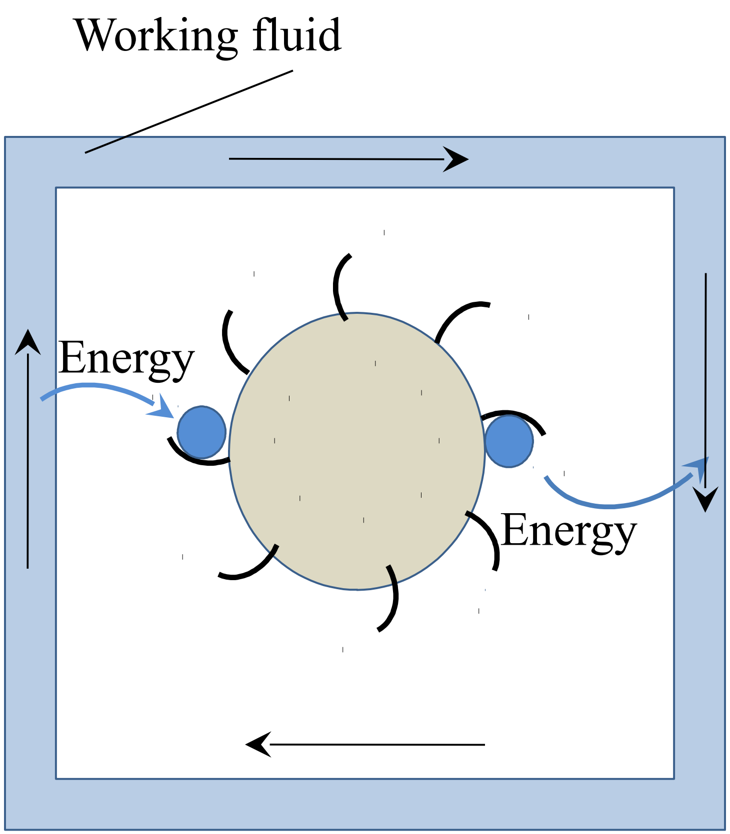
$$= 1 - \frac{\left(r_p\, r_c^{\gamma} - 1\right)}{\left\{\left(r_p\, r^{\gamma - 1} - r^{\gamma - 1}\right) + \gamma\left(r_p\, r_c\, r^{\gamma - 1} - r_p\, r^{\gamma - 1}\right)\right\}}$$

$$\eta_{th}\ 1 - \frac{1}{r^{\gamma - 1}}\left\{\frac{r_p\, r_c^{\gamma} - 1}{\left(r_p - 1\right) + \gamma r_p\left(r_c - 1\right)}\right\}$$

Stirling and Ericsson cycles

- The ideal Otto and Diesel cycles are internally reversible, but not totally reversible.
- Hence their efficiencies will always be less than that of Carnot efficiency.
- For a cycle to approach a Carnot cycle, heat addition and heat rejection must take place isothermally.
- Stirling and Ericsson cycles comprise of isothermal heat addition and heat rejection.

Regeneration



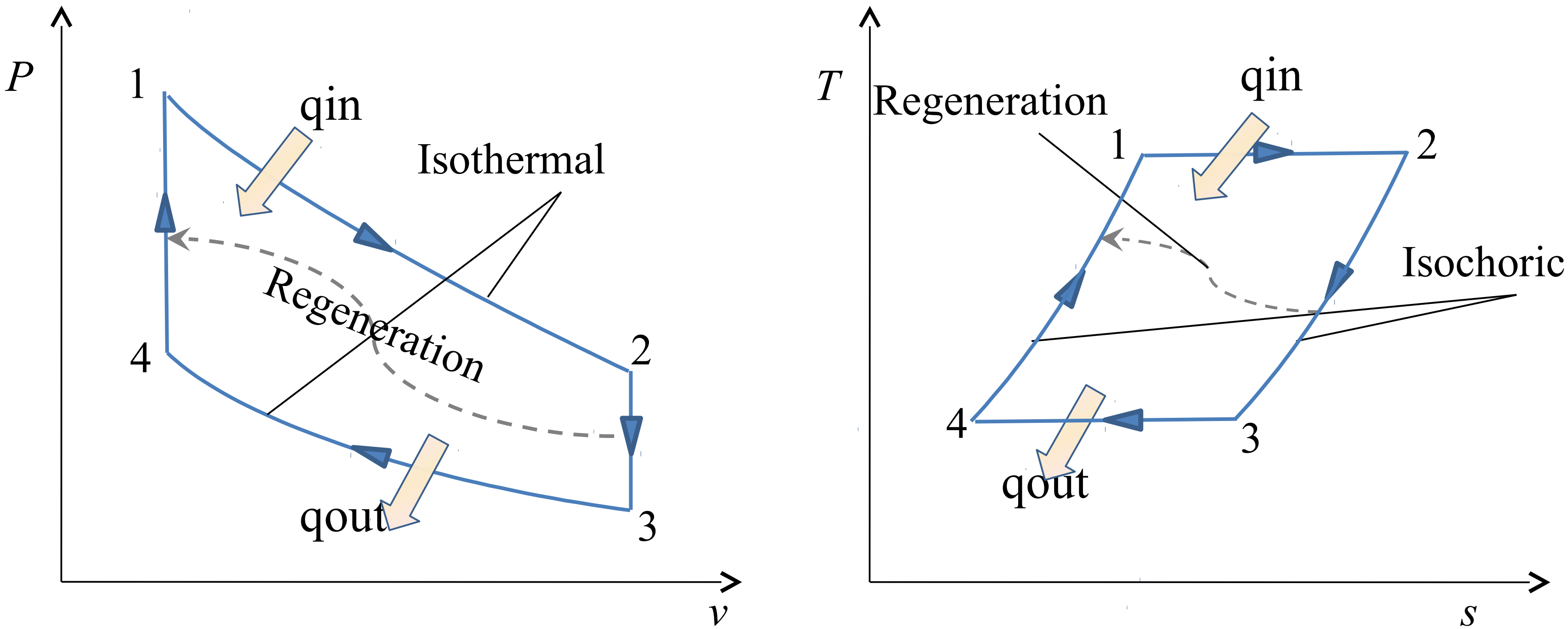
Concept of a regenerator

- Both these cycles also have a regeneration process.
- Regeneration, a process during which heat is transferred to a thermal energy storage device (called a regenerator) during one part of the cycle and is transferred back to the working fluid during another part of the cycle.

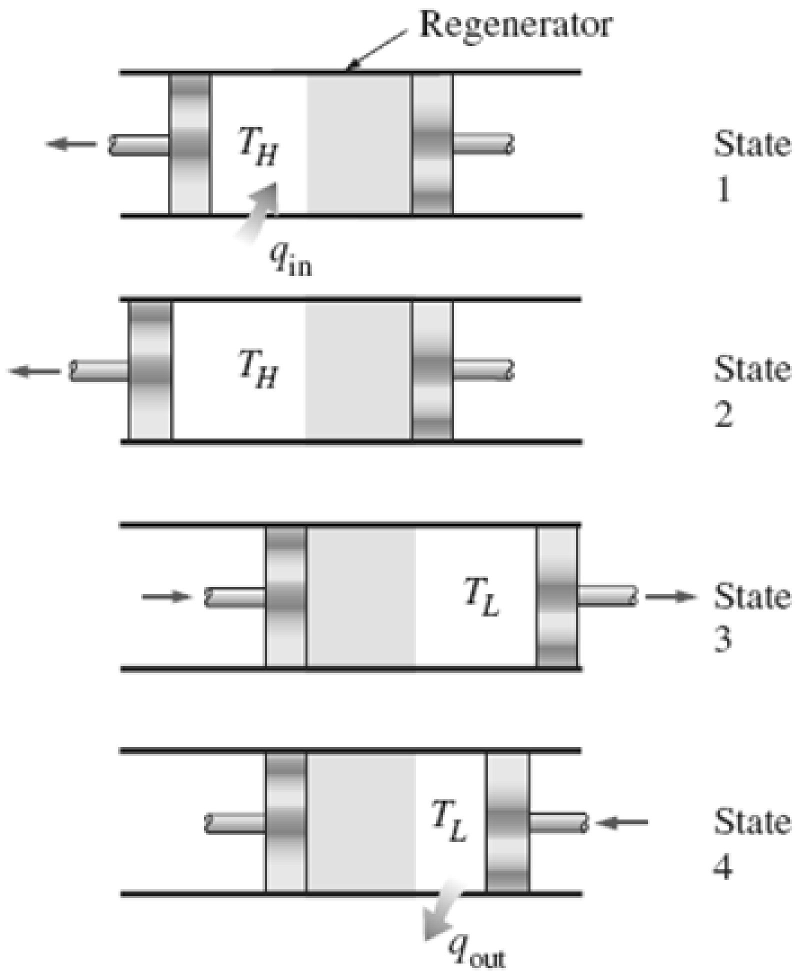
Stirling cycle

- Consists of four totally reversible processes:
  - 1-2 T = constant, expansion (heat addition from the external source)
  - 2-3 v = constant, regeneration (internal heat transfer from the working fluid to the regenerator)
  - 3-4 T= constant, compression (heat rejection to the external sink)
  - 4-1 v = constant, regeneration (internal heat transfer from the regenerator back to the working fluid)

Stirling cycle

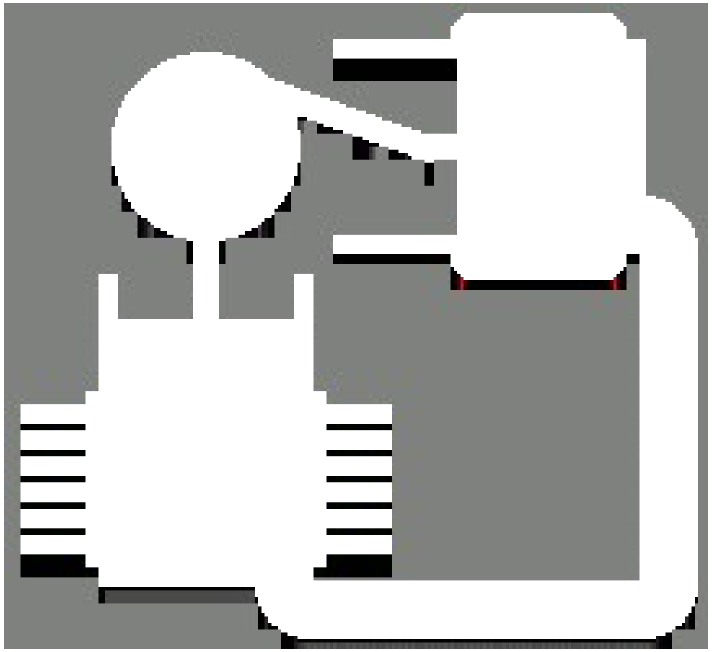


Stirling cycle on *P-v* and *T-s* diagrams



The execution of the Stirling cycle.

- Both pistons are moved at the same time to keep the volume constant
- Isothermal heat addition at TH
- Isothermal heat rejection at TL
- Regenerator (porous plug with a high thermal capacity)
- Mass of the working fluid within the regenerator negligible
- The second constant volume process takes place at a smaller volume than the first
- The net heat transfer during the regenerator is zero during the cycle



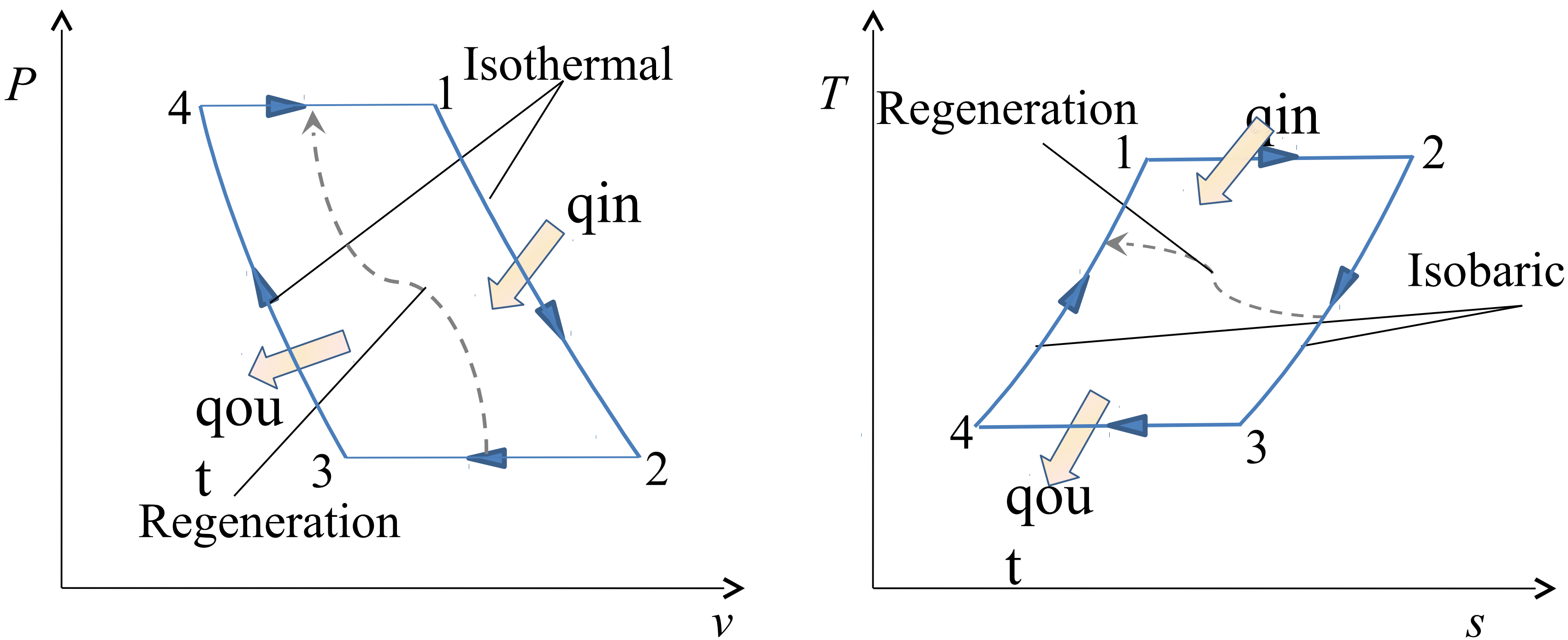
Stirling cycle: alpha version

Stirling cycle: beta version

Ericsson cycle

- Consists of four totally reversible processes:
  - 1-2 T = constant, expansion (heat addition from the external source)
  - 2-3 P = constant, regeneration (internal heat transfer from the working fluid to the regenerator)
  - 3-4 T= constant, compression (heat rejection to the external sink)
  - 4-1 P = constant, regeneration (internal heat transfer from the regenerator back to the working fluid)

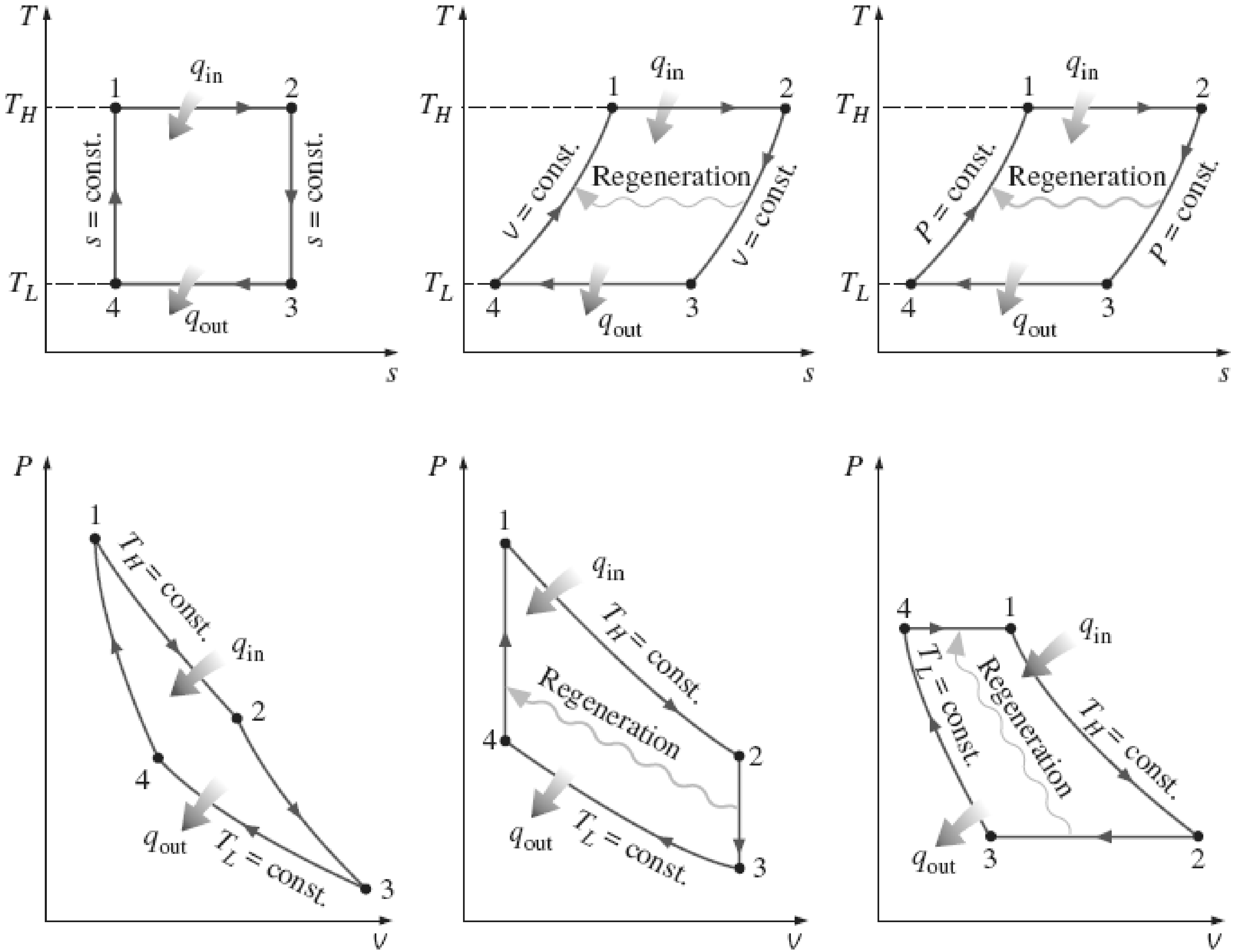
Ericsson cycle



Ericsson cycle on *P-v* and *T-s* diagrams

Stirling and Ericsson cycles

- Since both these engines are totally reversible cycles, their efficiencies equal the Carnot efficiency between same temperature limits.
- These cycles are difficult to realise practically, but offer great potential.
- Regeneration increases efficiency.
- This fact is used in many modern day cycles to improve efficiency.



(*a*) Carnot cycle (*b*) Stirling cycle (*c*) Ericsson cycle