Gas and Vapour Power Cycles

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Thermodynamic Cycles

- Two important areas of application for thermodynamics are power generation and refrigeration.

- Devices to produce power – Engines and Devices to produce Refrigeration – Refrigerators, Ai Conditioners, Heat Pumps

- Thermodynamic cycles - Gas and Vapour Cycles depending on phase of the working fluid

- In gas cycles, the working fluid remains in the whereas in vapor cycles the working fluid exists in the vapor phase during one part of the cycle and in the liquid phase during another part.

Power cycles

- Closed cycles or Open Cycles

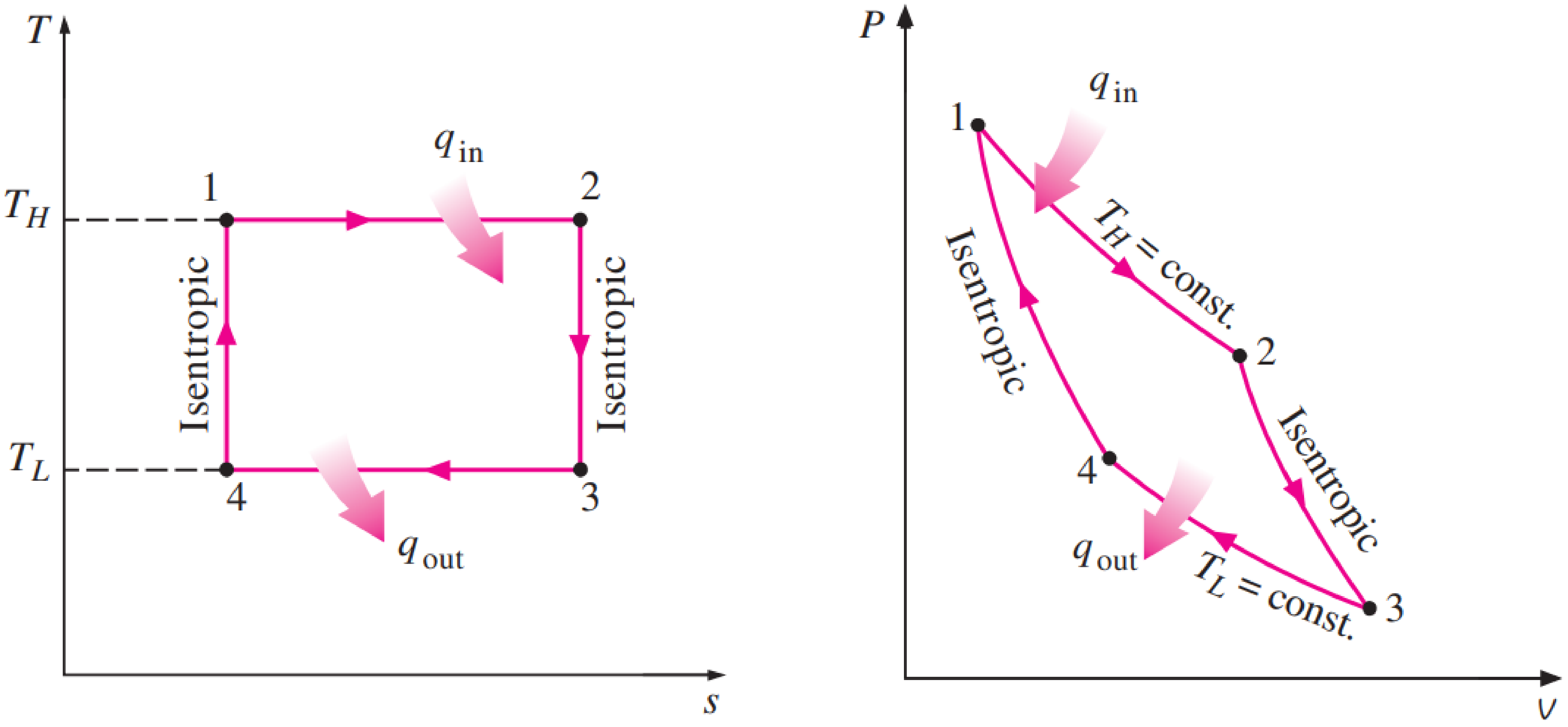
- Internal Engine or External Engines

- Ideal Cycles and Actual Cycle

- Heat engines : convert thermal energy to work, and their performance is expressed in terms of the thermal efficiency, η_{th}

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad \text{or} \quad \eta_{th} = \frac{w_{net}}{q_{in}}$$

Carnot Cycle



Carnot Cycle

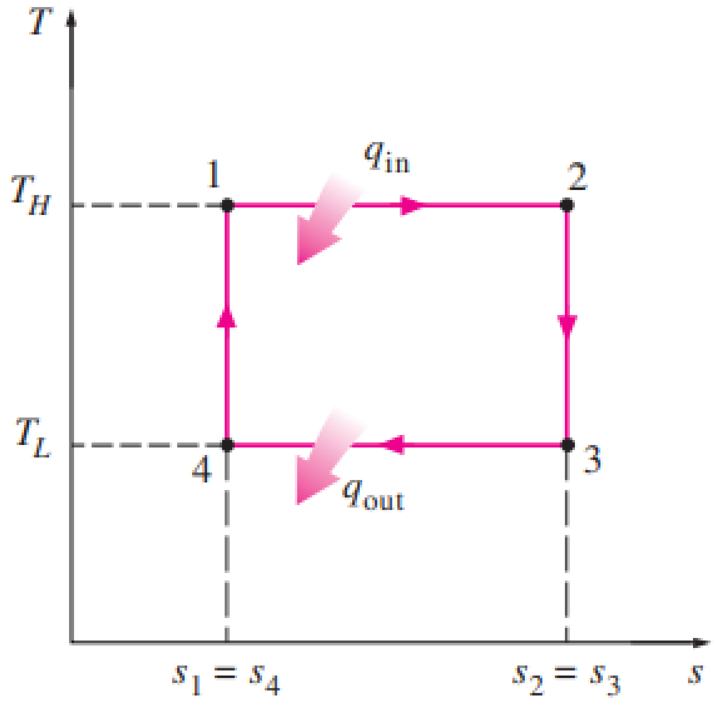
- The Carnot cycle : four reversible processes

- Isothermal heat addition, Isentropic expansion, Isothermal heat rejection, and Isentropic compression.

$$\eta_{\text{th,Carnot}} = 1 - \frac{T_L}{T_H}$$

- Reversible isothermal heat transfer : difficult

- Ideal Cycle, Efficiency depends on temperatures only



Air Standard Cycles

- In gas power cycles, the working fluid remains a gas throughout the entire cycle.

- Spark-ignition engines, diesel engines, and conventional gas turbines

- Engines : Energy is provided by burning a fuel within the system boundaries.

- Combustion Process : Composition of the working fluid changes from air and fuel to combustion products during the course of the cycle.

- Air is predominantly nitrogen that undergoes hardly any chemical reactions in the combustion chamber, the working fluid closely resembles air at all times.

Air Standard Cycles

- Even though internal combustion engines operate on a mechanical cycle (the piston returns to its starting position at the end of each revolution), the working fluid does not undergo a complete thermodynamic cycle.

- It is thrown out of the engine at some point in the cycle (as exhaust gases) instead of being returned to the initial state.

- Working on an open cycle is the characteristic of all internal combustion engines. The actual gas power cycles are rather complex.

- The actual gas power cycles are rather complex. To reduce the analysis to a manageable level, some assumptions area made which are commonly known as the air-standard assumptions

Air Standard Cycles – Assumptions

1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.

2. All the processes that make up the cycle are internally reversible.

3. The combustion process is replaced by a heat-addition process from an external source

4. The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.

5. Air has constant specific heats whose values are determined at 25 ^{o}C

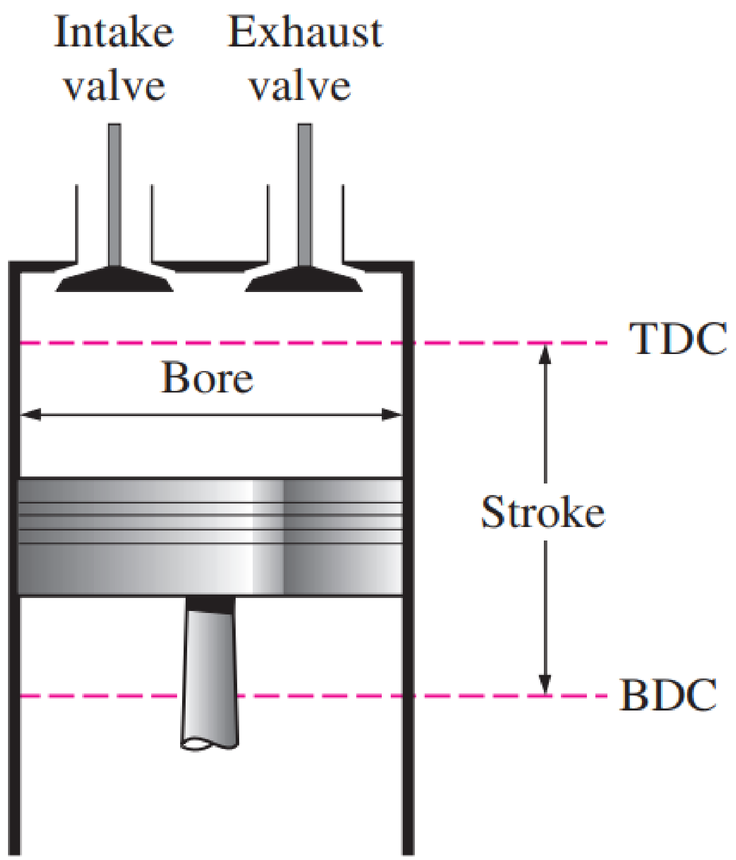
Reciprocating Engine

- TDC and BDC

- The distance between the TDC and the BDC : Stroke

- Diameter of the piston : bore

- Air or air–fuel mixture is drawn into the cylinder through the intake valve, and the combustion products are expelled from the cylinder through the exhaust valve



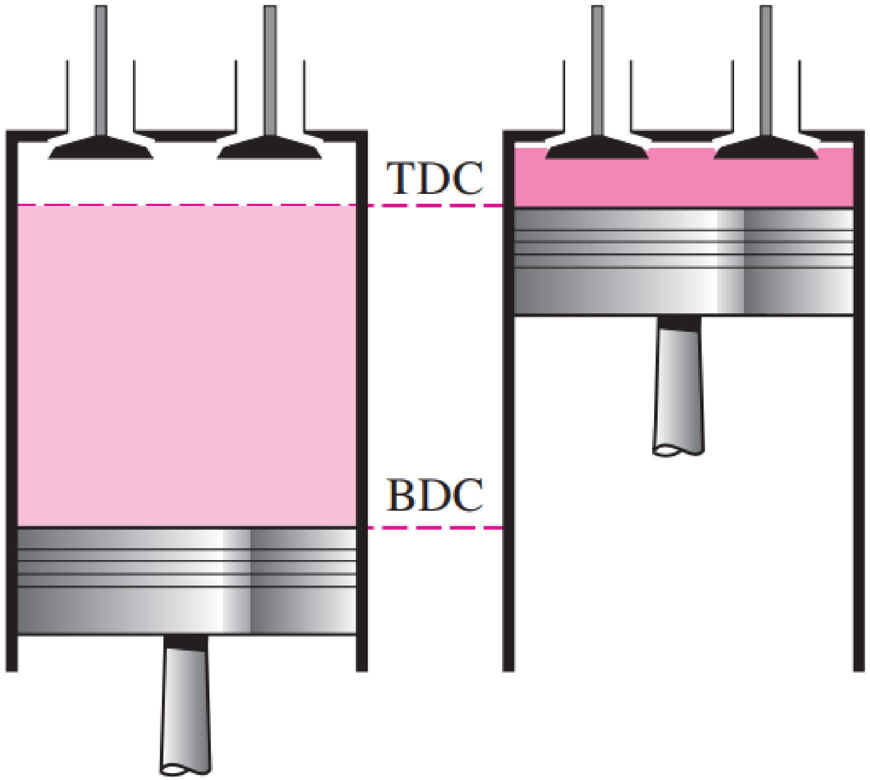
Reciprocating Engine

- Clearance Volume : The minimum volume formed in the cylinder when the piston is at TDC

- Displacement Volume : TDC and BDC

- Compression Ratio, *r*

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



(*a*) Displacement volume

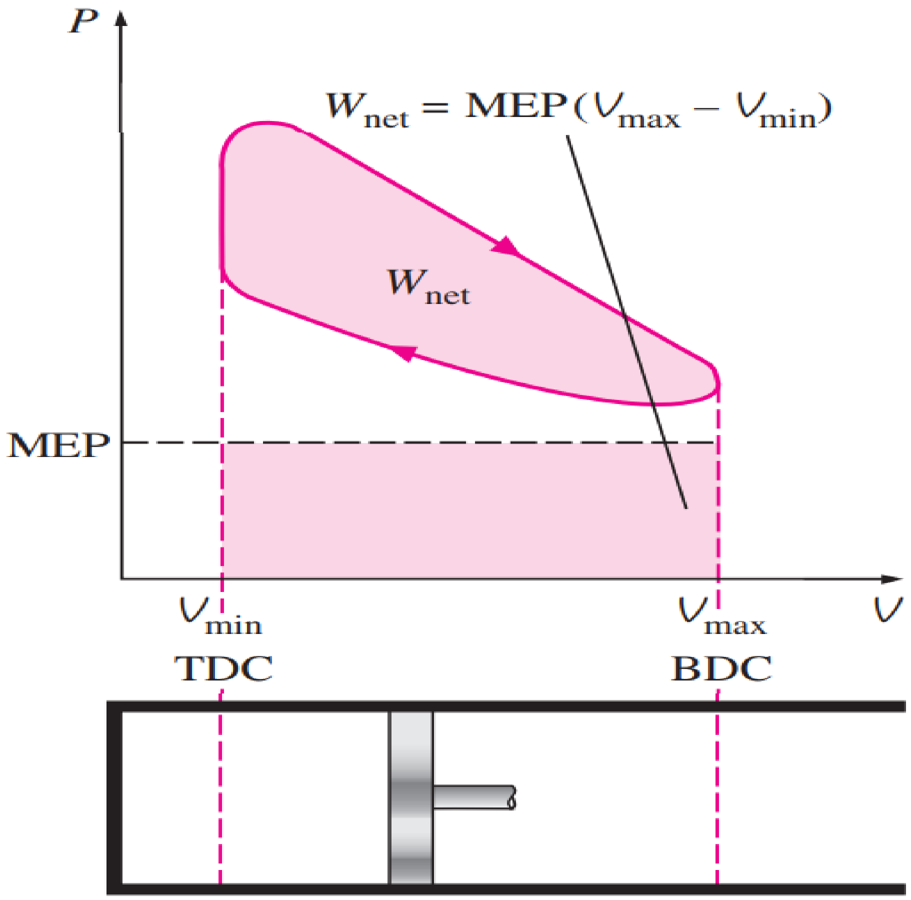
(*b*) Clearance volume

Reciprocating Engine - MEP

- Mean effective pressure (MEP) : Fictitious pressure that, if it acted on the piston during the entire power stroke, would produce the same amount of net work as in the actual cycle

- MEP can be used as a parameter to compare the performances of reciprocating engines of equal size.

$$W_{net} = \text{MEP x Piston area x Stroke}$$
$$= \text{MEP x Displacement volume}$$



$$\text{MEP} = \frac{W_{net}}{V_{max} - V_{min}} = \frac{w_{net}}{v_{max} - v_{min}} \qquad \text{(kPa)}$$

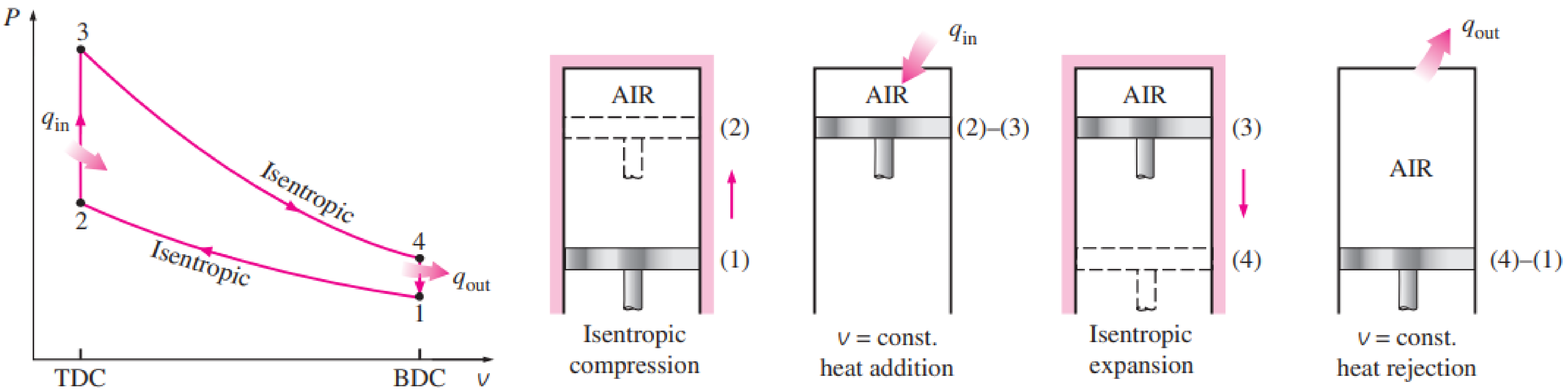
SI and CI Engines

- Reciprocating engines are classified as spark-ignition (SI) engines or compression-ignition (CI) engines, depending on how the combustion process in the cylinder is initiated.
- In SI engines, the combustion of the air–fuel mixture is initiated by a spark plug.
- In CI engines, the air–fuel mixture is self-ignited as a result of compressing the mixture above its self-ignition temperature.
- Otto and Diesel cycles

Otto Cycle

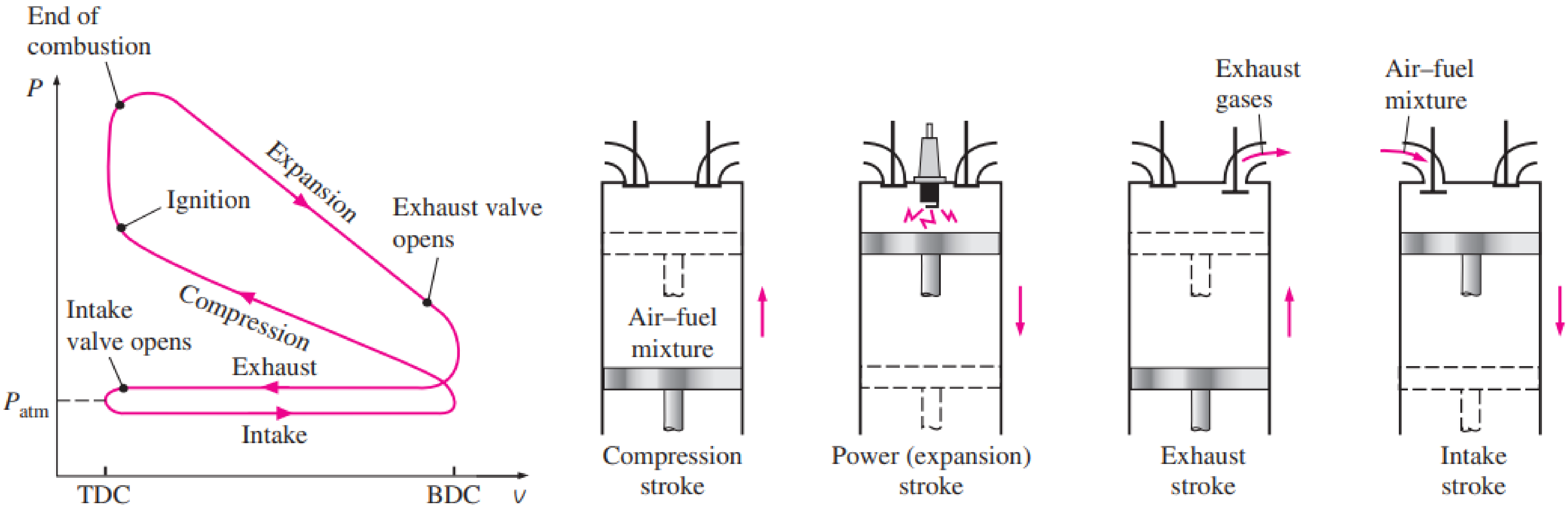
- The Otto cycle is the ideal cycle for spark-ignition reciprocating engines.
- Nikolaus A. Otto : 1876 in Germany using the cycle proposed by Frenchman Beau de Rochas in 1862. Used a 4-stroke machine
- SI Engines (most) : Piston executes four complete strokes (two mechanical cycles) within the cylinder, and the crankshaft completes two revolutions for each thermodynamic cycle.
- These engines are called four-stroke internal combustion engines.

Ideal Otto Cycle



(b) Ideal Otto cycle

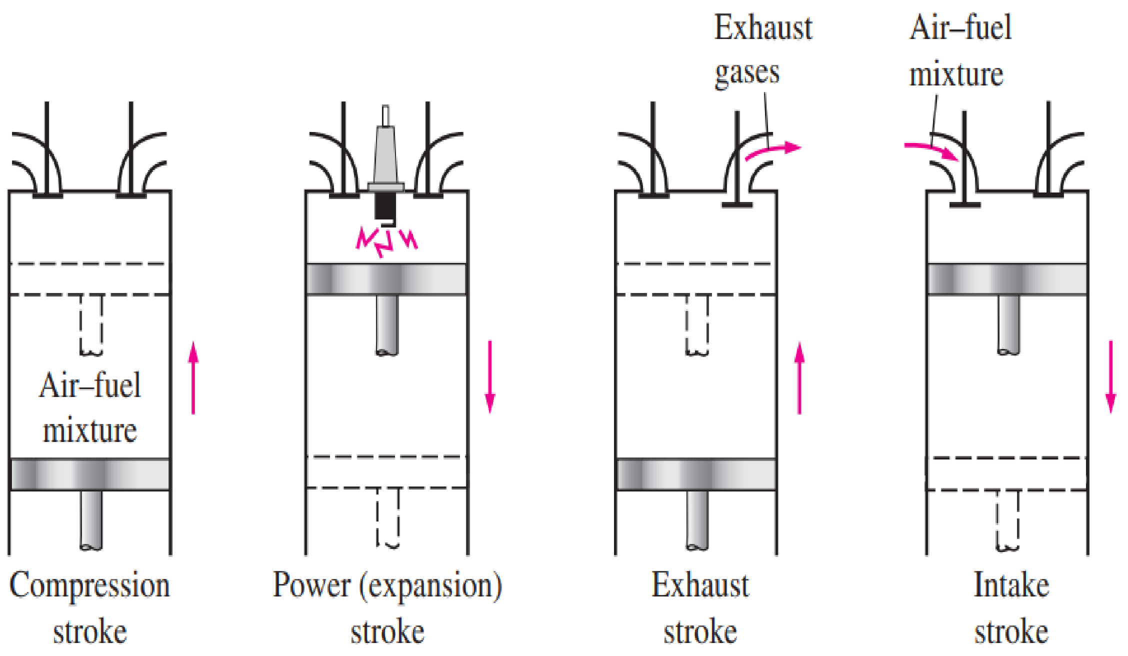
Actual Otto Cycle – 4 strokes



https://www.youtube.com/watch?v=0SPn5AxVx3k

How does it work ?

- Both valves closed and piston at BDC
- Compression stroke : the piston moves upward, compressing the air–fuel mixture.
- Before TDC, spark ignites and P and T of mixture increases.
- High pressure forces piston down - work is produced and this forces the crankshaft to rotate.
- This produces the useful work output during the expansion or power stroke.



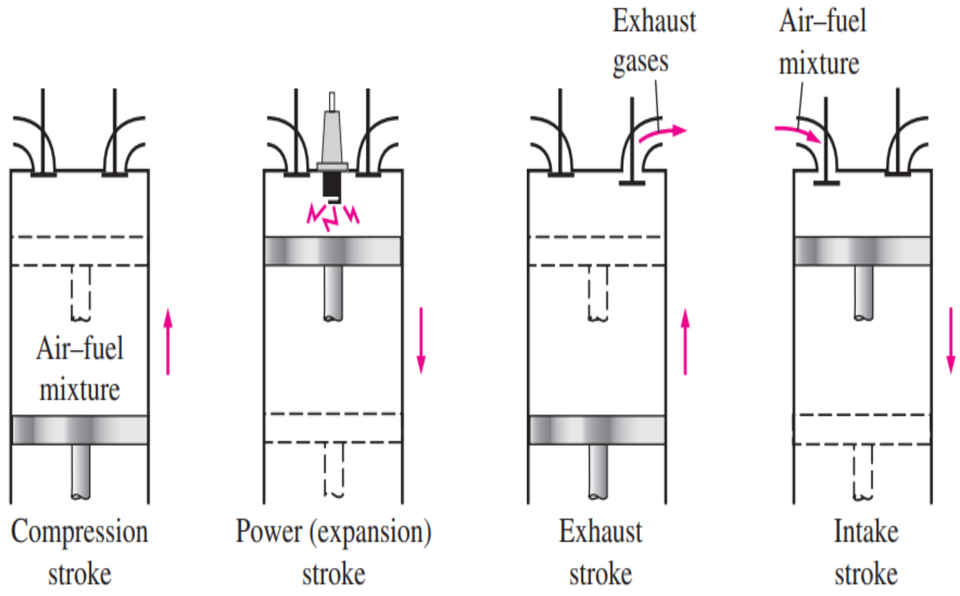
How does it work ?

- At the end of this stroke, the piston is at its BDC and the cylinder is filled with combustion products.

- Now the piston moves upward one more time, purging the exhaust gases through the exhaust valve (the exhaus stroke).

- Inlet valve opens : drawing in fresh air–fuel mixture through the intake valve (the intake stroke).

- The pressure in the cylinder is above the atmospheric pressure during the exhaust stroke and slightly below during the intake stroke.

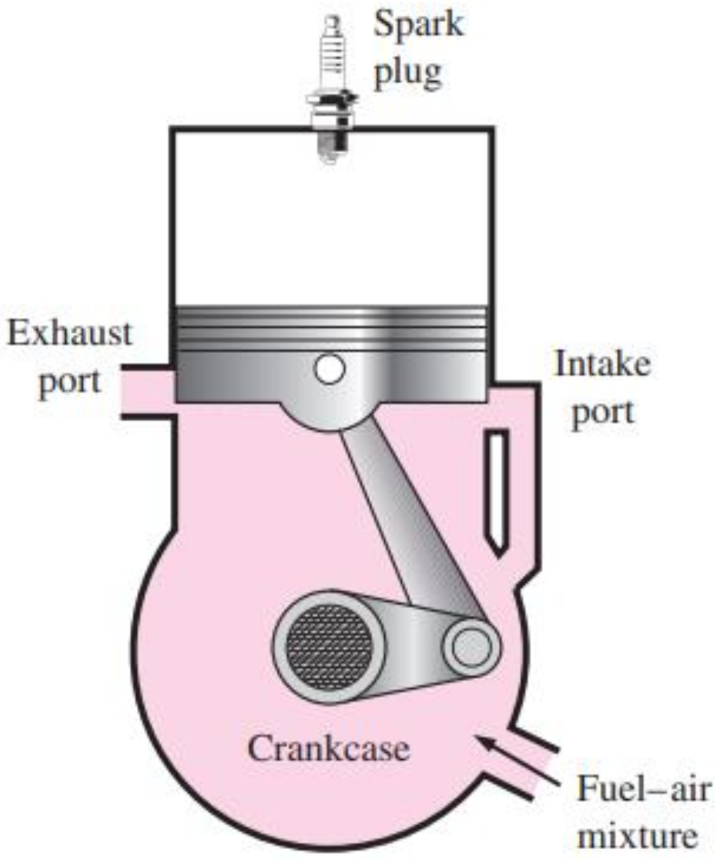


Two Stroke Engine

- In two-stroke engines, all four functions (Suction, compression, Expansion and Exhaust) described above are executed in just two strokes: the **power stroke and the compression stroke.**

- In these engines, the crankcase is sealed, and the outward motion of the piston is used to slightly pressurize the air–fuel mixture in the crankcase.

- The intake and exhaust valves are replaced by openings in the lower portion of the cylinder wall.

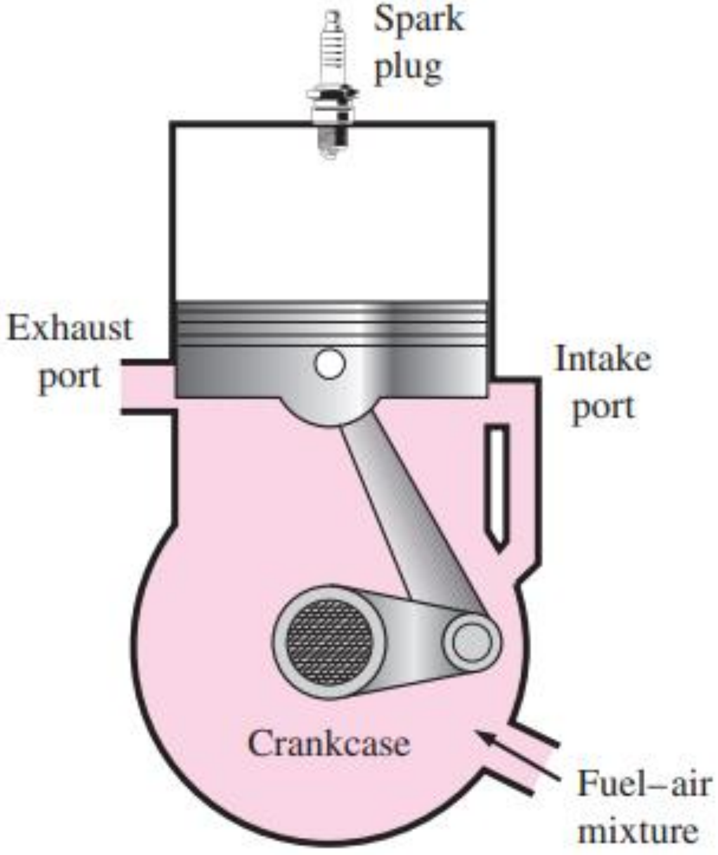


Two Stroke Engine

- 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 it uncovers the intake port, allowing the fresh air–fuel mixture to rush in and drive most of the remaining exhaust 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.



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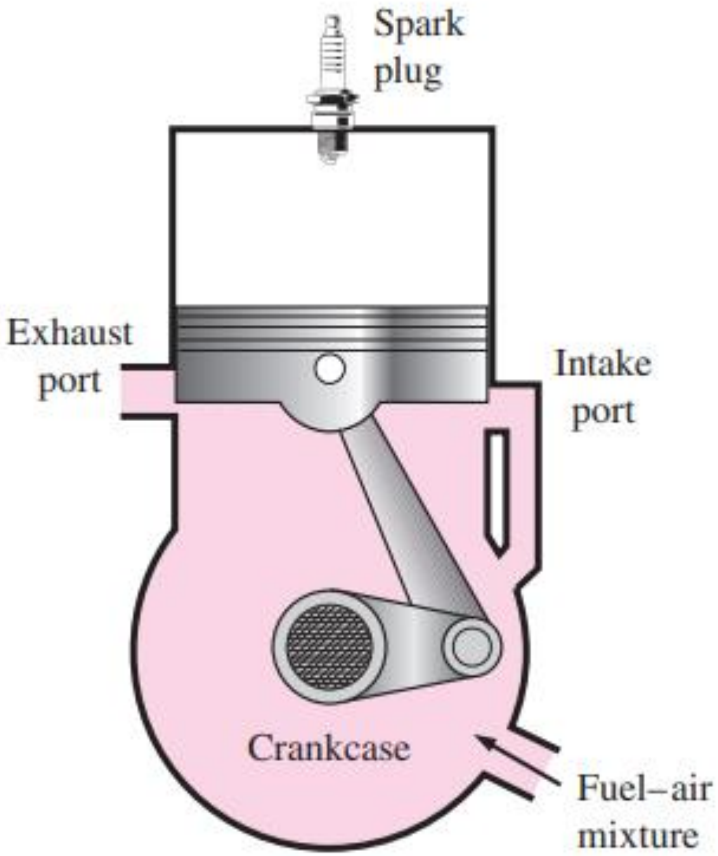
Two Stroke Engine

- The two-stroke engines are generally less efficient than their four-stroke counterparts.

- This is due to the fact that there is incomplete expulsion of the exhaust gases and the partial expulsion of the fresh air–fuel mixture with the exhaust gases.

- However, they are relatively simple and inexpensive, and they have high power-to-weight and power-to-volume ratios, which make them suitable for applications requiring small size and weight.

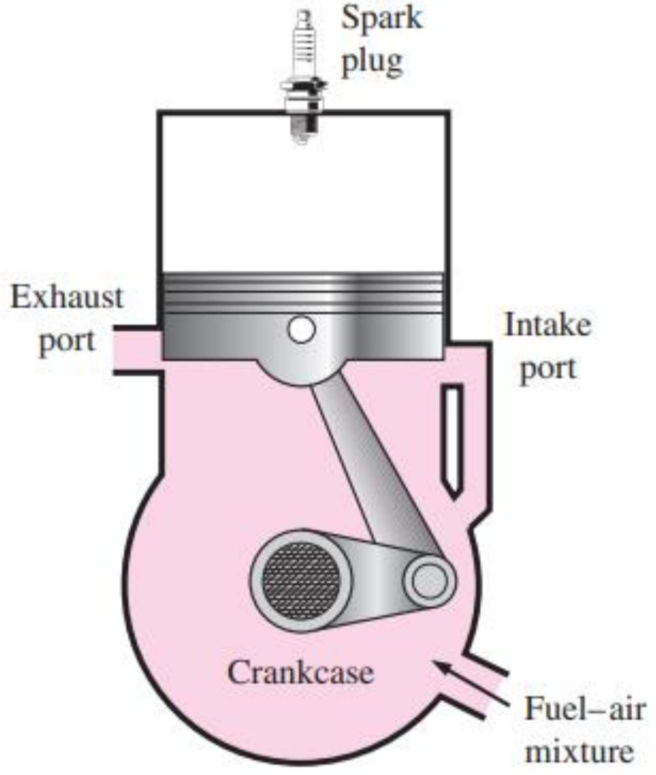


Two Stroke Engine

- Overall, a two-stroke engine contains two processes:

- **Compression stroke:** The inlet port opens, the air-fuel mixture enters the chamber and the piston moves upwards compressing this mixture. A spark plug ignites the compressed fuel and begins the power stroke.

- **Power stroke:** The heated gas exerts high pressure on the piston, the piston moves downward (expansion), waste heat is exhausted.



Two Stroke Engine

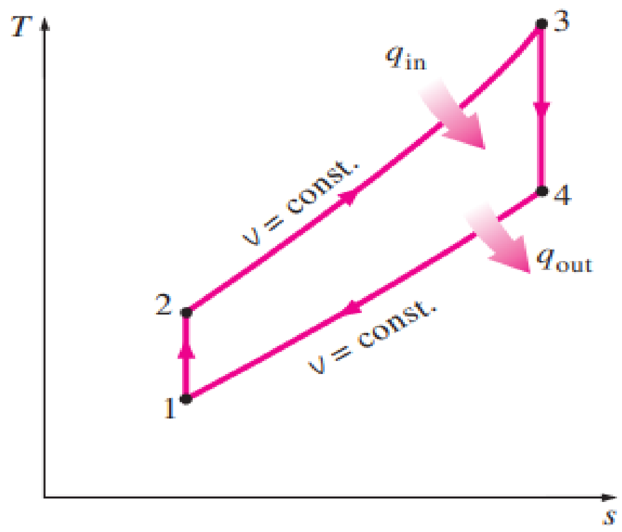
- New research and demands like high performance, fuel economy and emission controls, can be achieved using direct fuel injection, stratified charge combustion, and electronic controls

- For a given weight and displacement, a well-designed two-stroke engine can provide significantly more power than its four-stroke counterpart because two-stroke engines produce power on every engine revolution instead of every other one.

- Highly atomized fuel spray burns much more completely. The fuel is sprayed after the exhaust valve is closed : this prevents unburned fuel loss. With stratified combustion, the flame that is initiated by igniting a small amount of the rich fuel–air mixture near the spark plug propagates through the combustion chamber filled with a much leaner mixture : Cleaner combustion. Also, the advances in electronics ensures optimum operation under varying engine load and speed conditions.

Otto Cycle

- The thermodynamic analysis of the actual four-stroke or two-stroke cycles can be simplified significantly if the air-standard assumptions are utilized.



- The resulting cycle, which closely resembles the actual operating conditions, is the ideal Otto cycle.

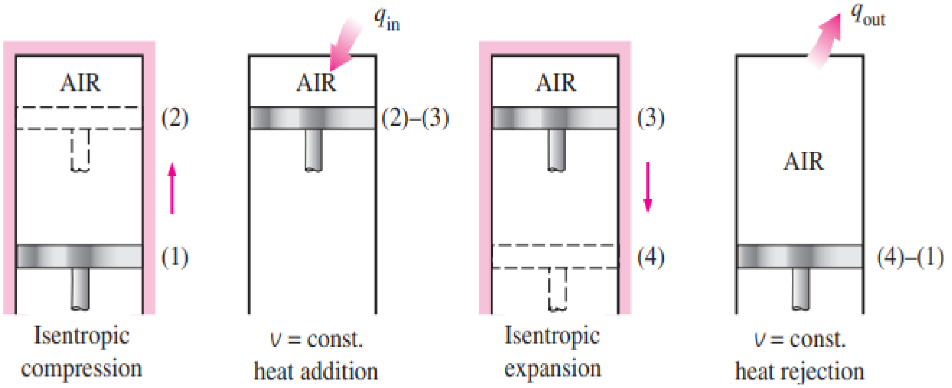
- It consists of four internally reversible processes:

  (a) 1-2 Isentropic compression

  (b) 2-3 Constant-volume heat addition

  (c) 3-4 Isentropic expansion

  (d) 4-1 Constant-volume heat rejection



Thermal Efficiency (η_{th}) of Otto Cycle

- Closed system and neglecting kinetic and potential energies. Also No work is involved during the two heat transfer processes – constant volume process.

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2) \qquad q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

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

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{k-1} = \left(\frac{v_3}{v_4}\right)^{k-1} = \frac{T_4}{T_3} \longrightarrow \eta_{th,Otto} = 1 - \frac{1}{r^{k-1}}$$

Where $r = \frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2}$

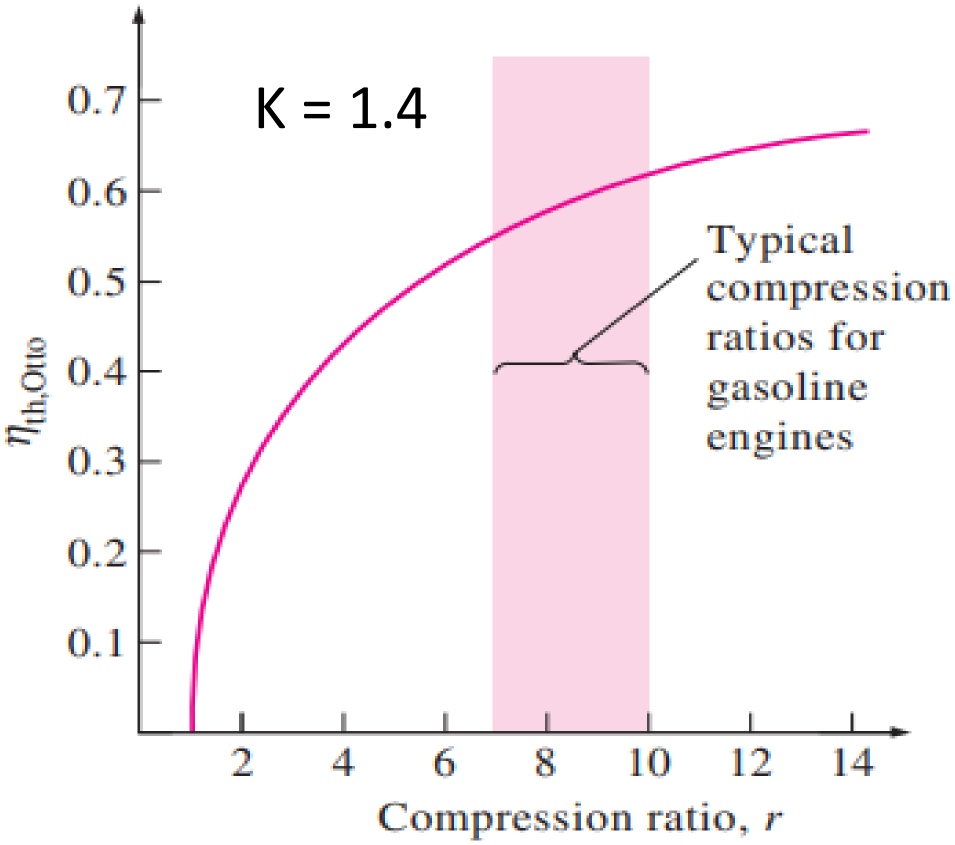
- *r* is the compression ratio and k is the specific heat ratio cp /cv.

Thermal Efficiency (η_{th}) of Otto Cycle

- η_{th} of an ideal Otto cycle depends on the compression ratio of the engine and the specific heat ratio of the working fluid.

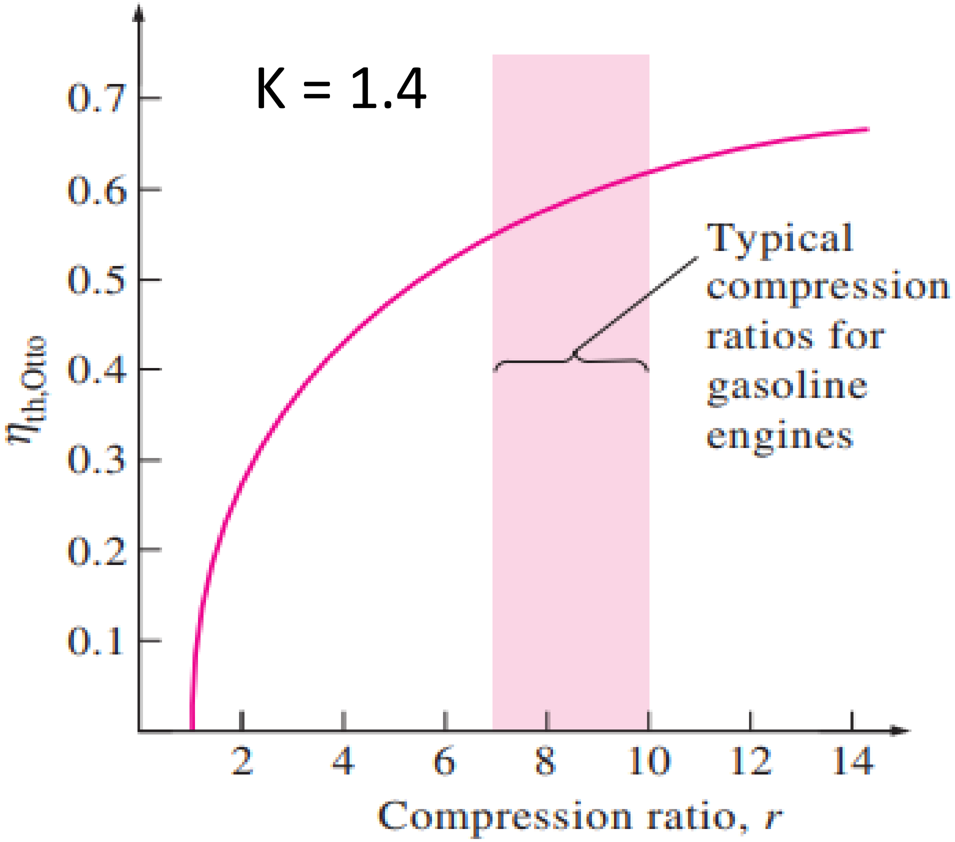
- The thermal efficiency of the ideal Otto cycle increases with both the compression ratio and the specific heat ratio. This is true with SI IC engines.

- For a given compression ratio, η_{th} of an actual spark-ignition engine is less than that of an ideal Otto cycle because of the irreversibility, such as friction, and other factors such as incomplete combustion



Thermal Efficiency (η_{th}) of Otto Cycle

- η_{th} variation is rather steep at low compression ratios but flattens out starting with a compression ratio value of about 8.
- When high compression ratios are used, the temperature of the air–fuel mixture rises above the autoignition temperature of the fuel leading to Premature Ignition. This produces an audible noise - ***Engine Knock.***
- Autoignition in spark-ignition engines should be avoided as it hurts performance and can cause engine damage – upper limit on ***r***



Thermal Efficiency (η_{th}) of Otto Cycle

- Gasoline Blends : Improvement of η_{th} by using higher compression ratios (up to about 12) without facing the autoignition. They have good antiknock characteristics, such as gasoline mixed with **tetraethyl lead**.

- Octane rating : Measure of the engine knock resistance of a fuel. Leaded gasoline, however, has a very undesirable side effect: it forms compounds during the combustion process that are hazardous to health and pollute the environment.

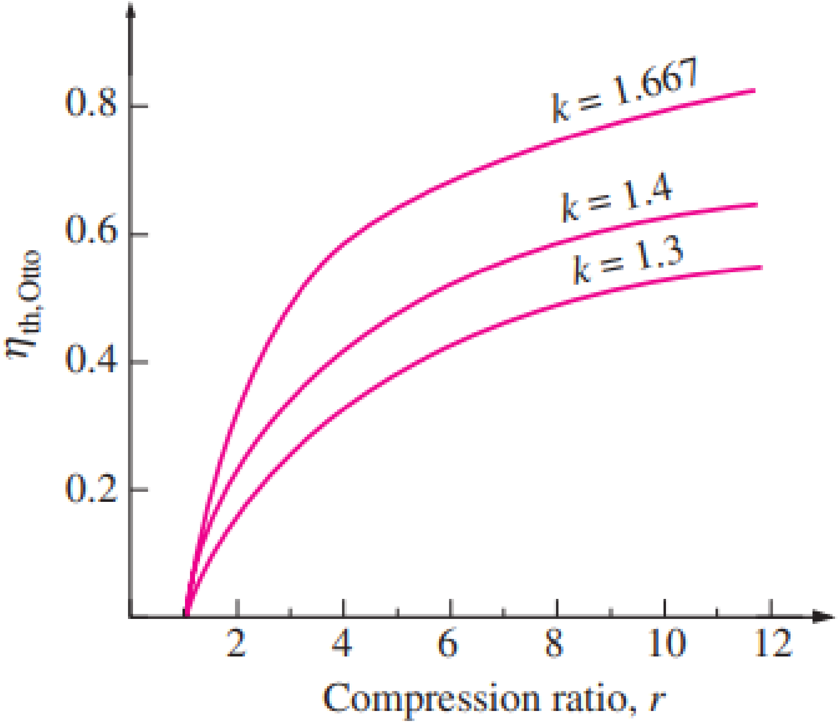
- Phasing out of leaded gasoline : Unable to use lead, the refiners developed other techniques to improve the antiknock characteristics of gasoline.

- Today, high octane fuels are available, we can raise the compression ratios. Also, owing to the improvements in other areas (reduction in overall weight, aero dynamic design, etc.), today's cars have better fuel economy (milage)

Thermal Efficiency (η_{th}) of Otto Cycle

- The second parameter affecting $\boldsymbol{\eta}_{\mathbf{th}}$ is the specific heat ratio *k*. Monoatomic Gases are preferred

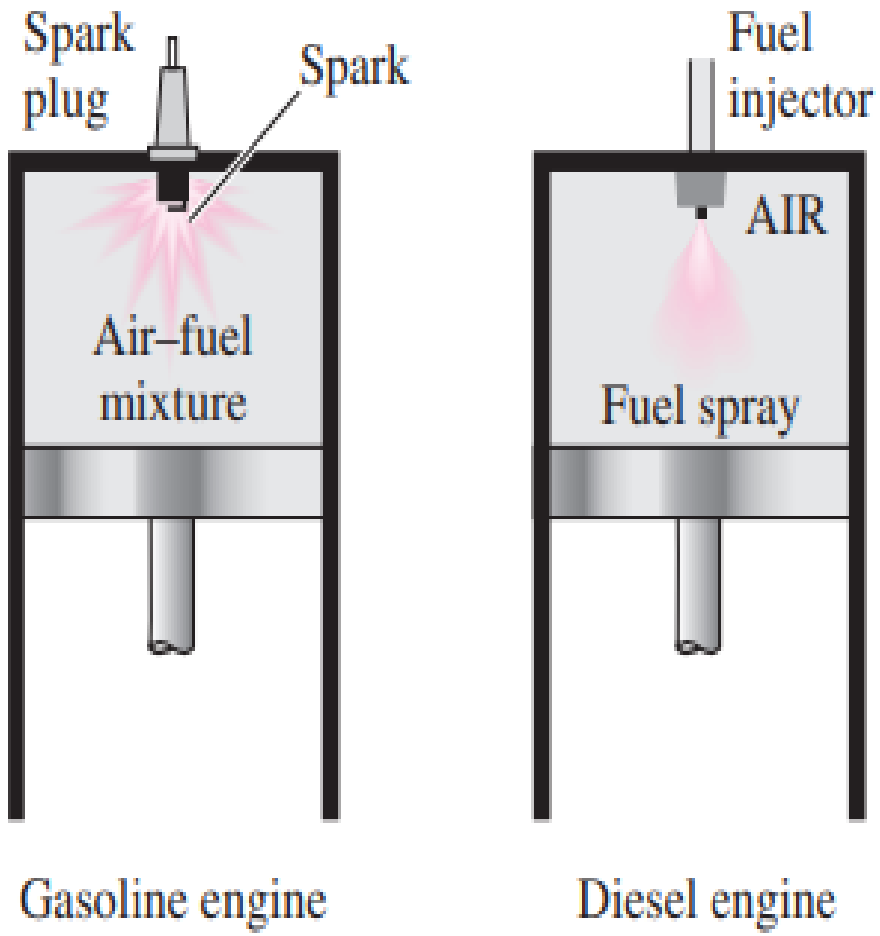
- At room temperature *k* is 1.4 for air, 1.3 for carbon dioxide, and 1.2 for ethane. The working fluid in actual engines contains larger molecules such as carbon dioxide, and the specific heat ratio decreases with temperature, which is one of the reasons that the actual cycles have lower thermal efficiencies than the ideal Otto cycle.



- The thermal efficiencies of actual spark-ignition engines range from about 25 to 30 percent.

Diesel Cycle – Compression Ignition Cycle

- CI Engine Or Diesel Engine
- Rudolph Diesel proposed in 1890s : Different in method of initiating combustion.
- SI : 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.
- CI engines : Air is compressed to a temperature that is above the autoignition temperature of the fuel, and combustion starts

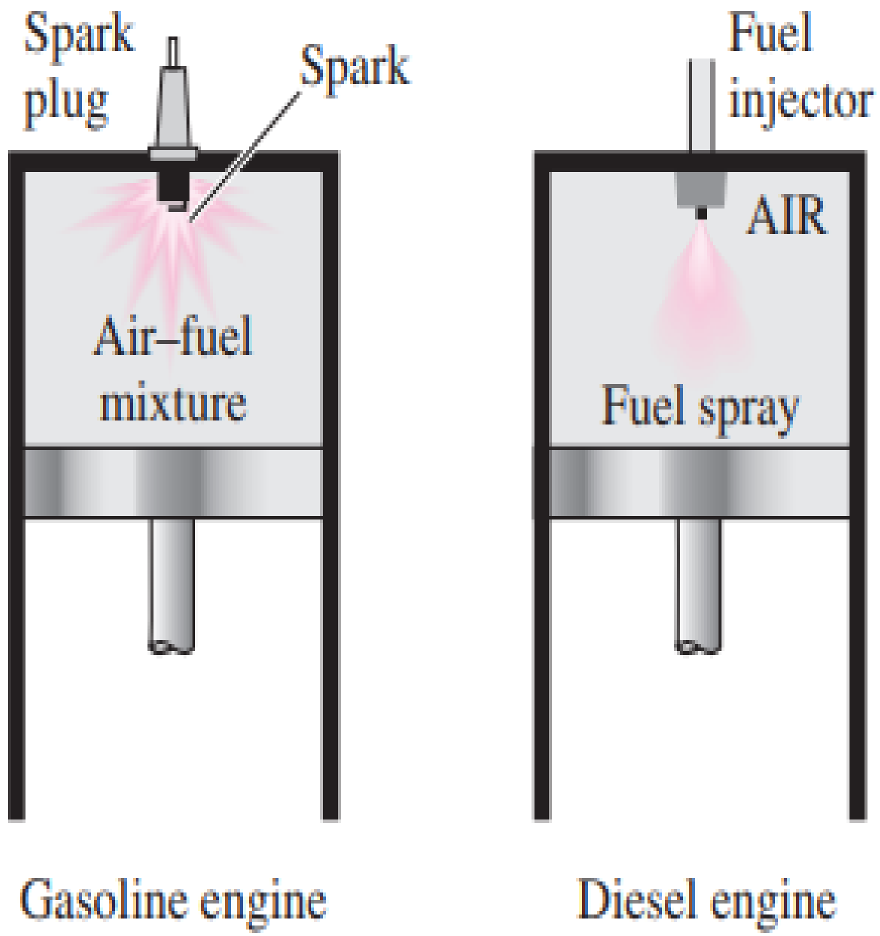


Diesel Cycle – Compression Ignition Cycle

- Spark plug and carburetor are replaced by a fuel injector in diesel engines

- SI or Otto : mixture of air and fuel is compressed during the compression stroke, and the compression ratios are limited by the onset of autoignition or engine knock.

- Diesel : Only air is compressed during the compression stroke, eliminating the possibility of autoignition. Therefore, diesel engines can be designed to operate at much higher compression ratios, typically between 12 and 24.



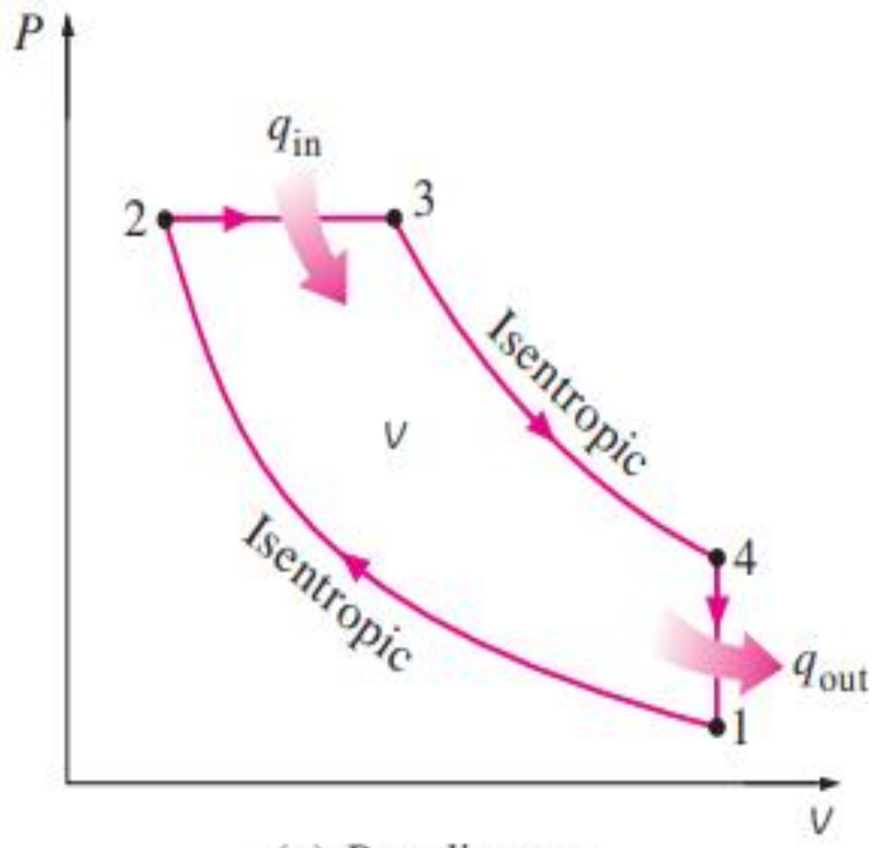
Diesel Cycle – Compression Ignition Cycle

- The fuel injection process in diesel engines starts when the piston approaches TDC and continues during the first part of the power stroke.

- Combustion process in these engines takes place over a **longer interval**.

- Due to this, the combustion process in the ideal Diesel cycle is approximated as a **constant-pressure heat-addition** process – differ from Otto.

- Rest processes are as Otto : 1-2 is isentropic compression, 3-4 is isentropic expansion, and 4-1 is constant-volume heat rejection.



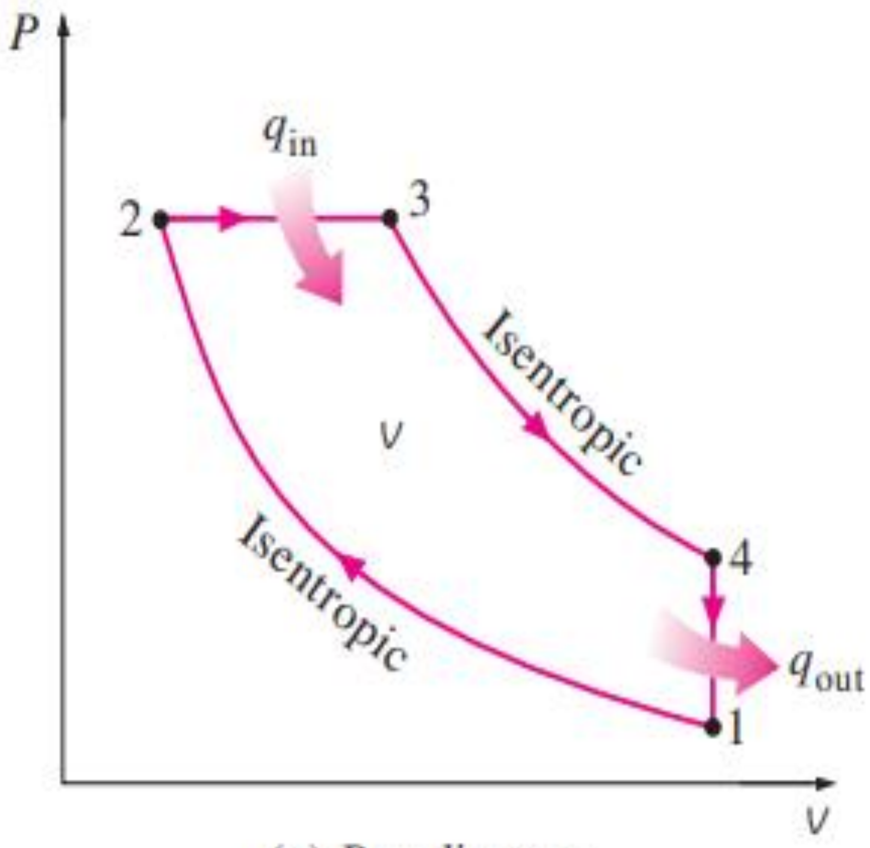
(a) P- v diagram

Diesel Cycle – Compression Ignition Cycle

- Diesel cycle is executed in a closed system, q_{in}, the amount of heat transferred to the working fluid at constant pressure and rejected from it at constant volume :

$$q_{in} - w_{b,out} = u_3 - u_2 \rightarrow q_{in} = P_2(v_3 - v_2) + (u_3 - u_2)$$
$$= h_3 - h_2 = c_p(T_3 - T_2)$$

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

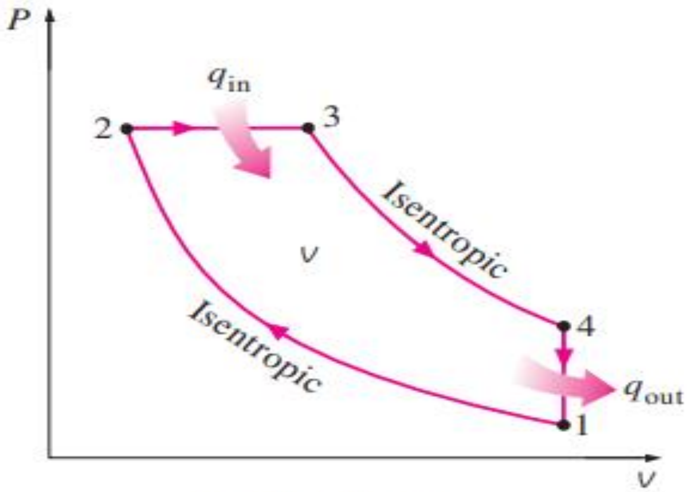


(a) P- v diagram

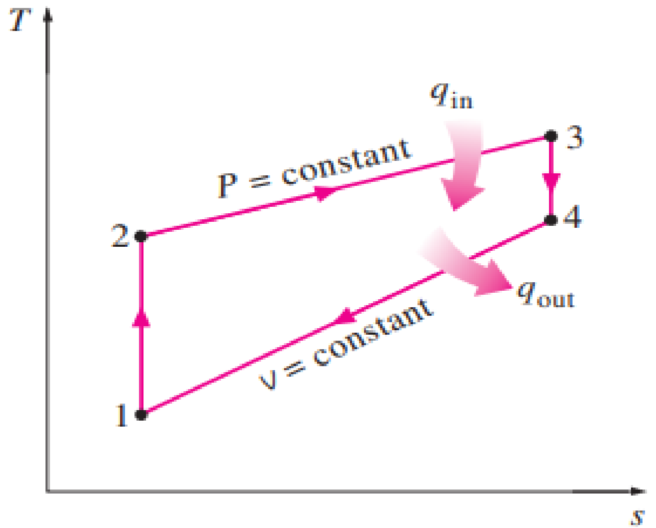
Diesel Cycle – Compression Ignition Cycle

$$\eta_{\text{th,Diesel}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)}$$

- Process 1-2 $\quad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$
- $T_2 = T_1(r)^{k-1}$ $\quad \frac{T_1}{T_2} = \frac{1}{(r)^{k-1}}$
- Process 2-3 - $\quad \frac{V_2}{T_2} = \frac{V_3}{T_3}$; $\quad \frac{T_3}{T_2} = \frac{V_3}{V_2} = r_c$
- Cutoff ratio r_c, as the ratio of the cylinder volumes after and before the combustion process and r is compression ratio



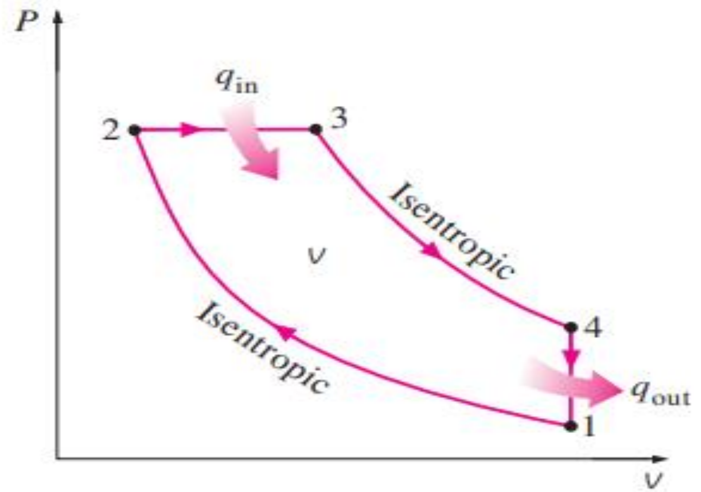
(a) P- v diagram



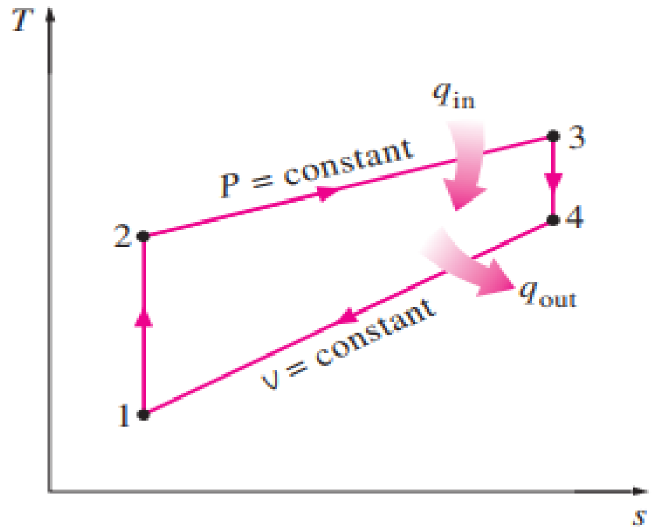
(b) T-s diagram

Diesel Cycle – Compression Ignition Cycle

- Process 3-4 : $\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{k-1}$; $= \left(\frac{V_3}{V_2} \times \frac{V_2}{V_4}\right)^{k-1}$
- $\frac{T_4}{T_3} = \left(\left(\frac{r_c}{r}\right)^{k-1}\right)$ where, $\frac{V_3}{V_2} = r_c$ and $\frac{V_4}{V_2} = r$ as $V_4 = V_1$
- $\eta_d = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{k\,T_2\left(\frac{T_3}{T_2} - 1\right)}$; $\eta_d = 1 - \frac{\left(\frac{T_4}{T_3} \times \frac{T_3}{T_2} \times \frac{T_2}{T_1} - 1\right)}{k\,(r)^{k-1}(r_c - 1)}$
- $\eta_d = 1 - \frac{\left(\left(\frac{r_c}{r}\right)^{k-1} \times r_c \times (r)^{k-1} - 1\right)}{k(r)^{k-1}(r_c - 1)}$;
- $\boldsymbol{\eta_d = 1 - \frac{1}{(r)^{k-1}}\left[\frac{(r_c{}^k - 1)}{k(r_c - 1)}\right]}$



(a) P- v diagram



(b) T-s diagram

Diesel Cycle – Compression Ignition Cycle

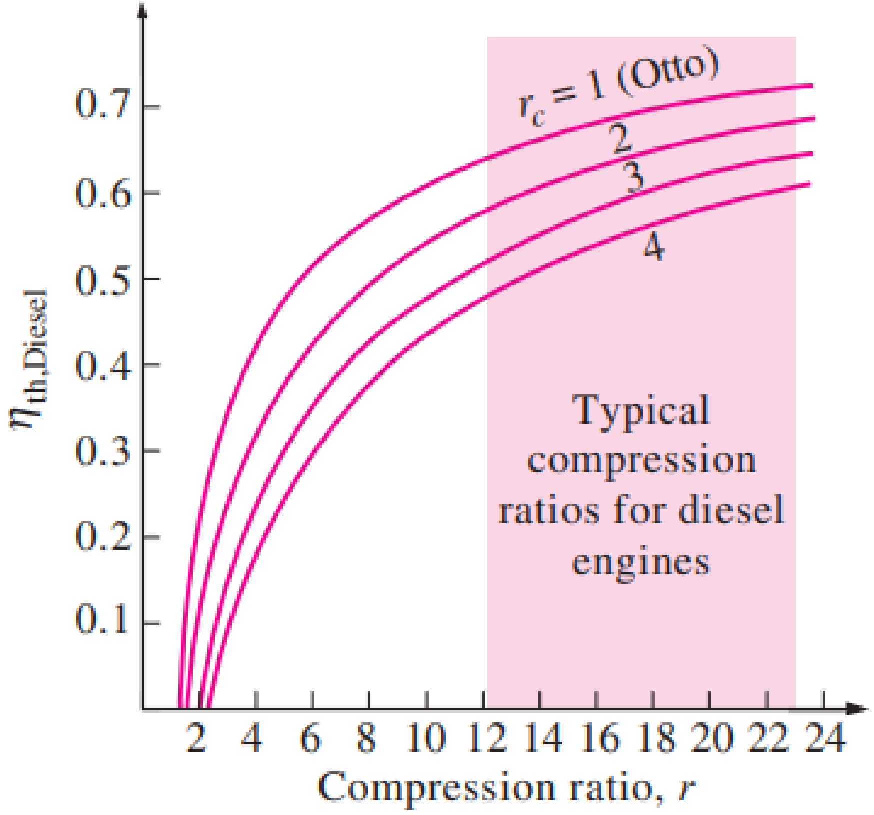
- Efficiency of a Diesel cycle differs from the efficiency of an Otto cycle by the quantity in the brackets. This quantity is always greater than 1.

$$\eta_{\text{th,Otto}} > \eta_{\text{th,Diesel}}$$

For the same compression ratio.

- As the cutoff ratio decreases, the efficiency of the Diesel cycle increases

- For the limiting case *of* $r_c = 1$, the quantity in the brackets becomes unity and the efficiencies of the Otto and Diesel cycles become identical.



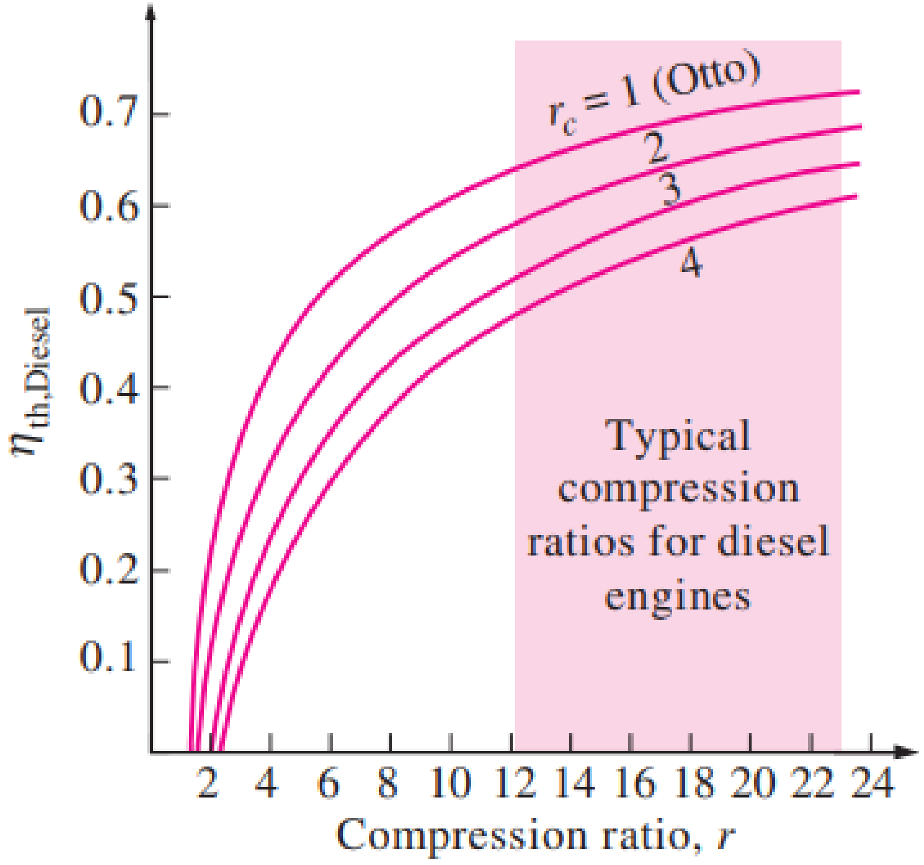
Diesel Cycle – Compression Ignition Cycle

- The diesel engines operate at much higher compression ratios and thus are usually more efficient than SI engines.

- 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.

- Thermal efficiencies of large diesel engines range from about 35 to 40 percent.

- Higher efficiency and lower fuel costs of diesel engines : Used where large amounts of power.



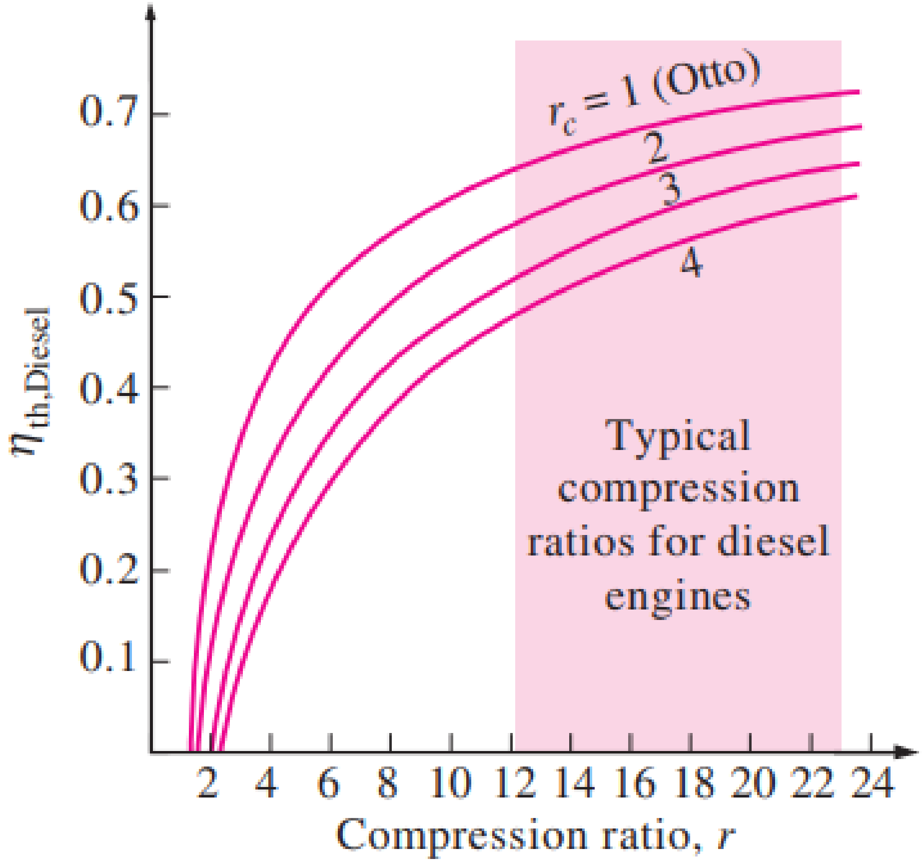
Diesel Cycle – Compression Ignition Cycle

- They are used mostly in locomotive engines, emergency power generation units, large ships, and heavy trucks.

- Brake Horsepower and Torque

- Medium Diesel Engines : 188 to 750 kilowatts. The power output of medium-speed diesel engines can be as high as 21,870 kW

- The engine power of [Hyundai Venue]() petrol version is 81.80bhp@6000rpm.

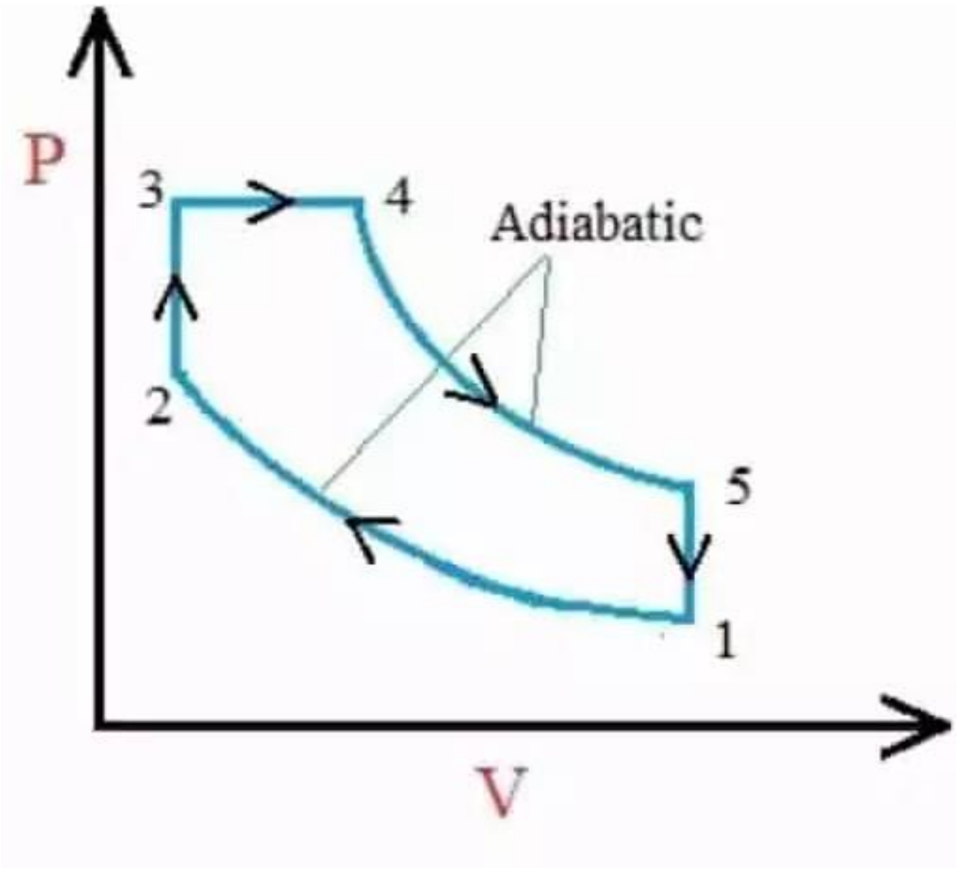


Dual Cycle

- Constant Volume and pressure processes is a simplistic assumption and not realistic.

- Realistic could be that the combustion process in both gasoline and diesel engines as a combination of two heat-transfer processes, one at constant volume and the other at constant pressure.

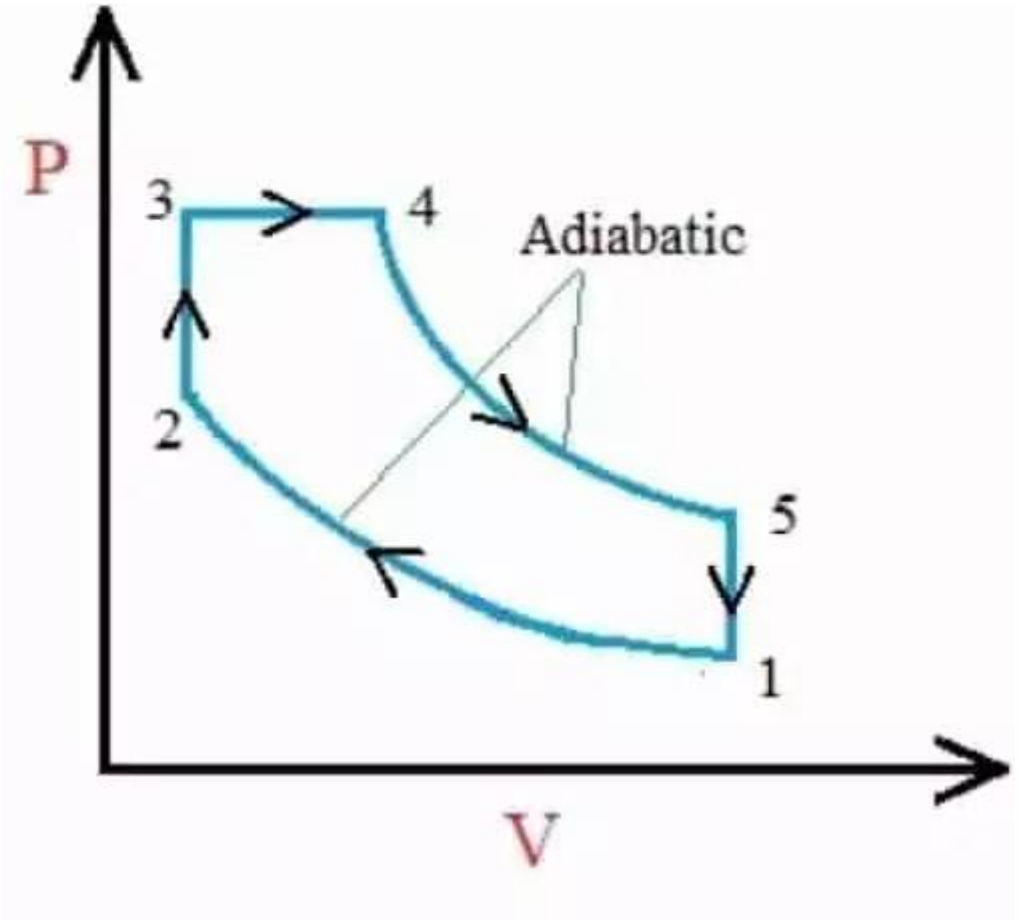
- Dual cycle : Both the Otto and the Diesel cycles can be obtained as special cases of the dual cycle.



Dual Cycle

- $Q_{in} = C_v(T_3 - T_2) + C_p(T_4 - T_3)$
- $Q_{out} = C_v(T_5 - T_1)$
- $\eta_{dual} = 1 - \frac{Q_{in}}{Q_{out}}$
- $\eta_{dual} = 1 - \frac{C_v(T_5 - T_1)}{C_v(T_3 - T_2) + C_p(T_4 - T_3)}$
- $\eta_{dual} = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + k(T_4 - T_3)}$

$$\eta_{dual} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_p r_c{}^{k} - 1}{(r_p - 1) + k r_p (r_c - 1)}\right]$$



Dual Cycle

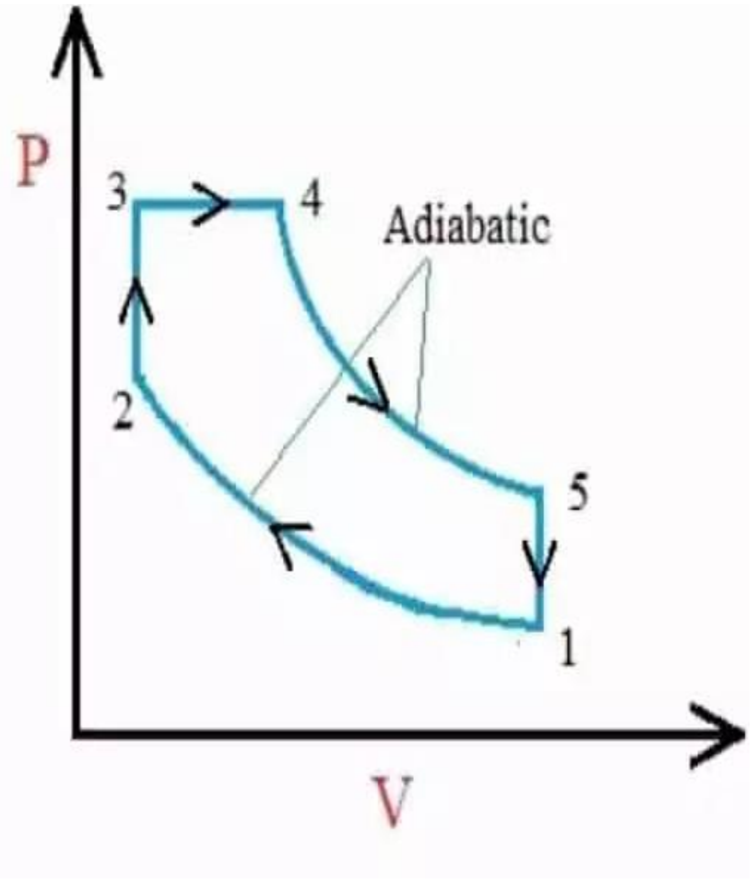
- **Process 1-2 :** $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\mathrm{k}-1}$; $\frac{T_2}{T_1} = (r)^{\mathrm{k}-1}$

- **Process 2-3 :** $r_p = \frac{p_3}{p_2}$; $\frac{T_3}{T_2} = \frac{p_3}{p_2} = r_p$; $\frac{T_3}{T_2} = r_p$

- **Process 3-4 :** $\frac{T_4}{T_3} = \frac{V_4}{V_3} = r_c$; $\frac{T_4}{T_3} = r_c$

- **Process 4-5 :** $\frac{T_5}{T_4} = \left(\frac{\mathrm{V}_4}{\mathrm{V}_5}\right)^{\mathrm{k}-1}$; $\frac{\mathrm{V}_4}{\mathrm{V}_5} = \frac{\mathrm{V}_4}{\mathrm{V}_1} = \frac{\mathrm{V}_4}{\mathrm{V}_3} \times \frac{\mathrm{V}_3}{\mathrm{V}_1}$ **as** $\mathrm{V}_5 \equiv \mathrm{V}_1$

- Since $\mathrm{V}_3 = \mathrm{V}_2$; $\frac{\mathrm{V}_4}{\mathrm{V}_3} \times \frac{\mathrm{V}_2}{\mathrm{V}_1}$; $\frac{\mathrm{V}_4}{\mathrm{V}_5} = \frac{r_c}{r}$; $\frac{T_5}{T_4} = \left(\frac{r_c}{r}\right)^{\mathrm{k}-1}$



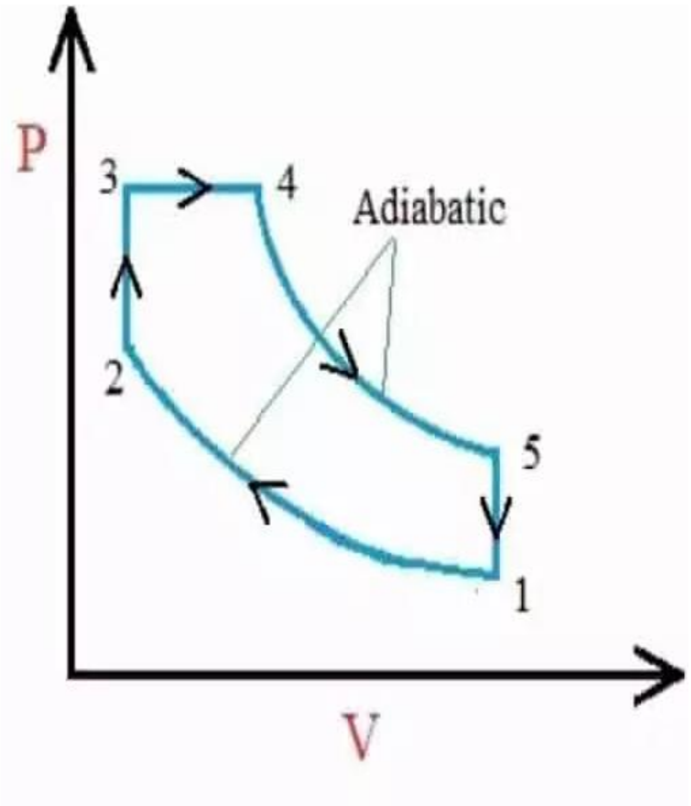
Dual Cycle

- $\eta_{dual} = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + k(T_4 - T_3)}$

- $\eta_{dual} = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + k(T_4 - T_3)}$; $\eta_{dual} = 1 - \frac{T_1\left(\frac{T_5}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right) + kT_3\left(\frac{T_4}{T_3} - 1\right)}$

- $\eta_{dual} = 1 - \frac{T_1\left(\frac{T_5}{T_1} - 1\right)}{T_2\left[\left(\frac{T_3}{T_2} - 1\right) + k\frac{T_3}{T_2}\left(\frac{T_4}{T_3} - 1\right)\right]}$;

- $\eta_{dual} = 1 - \frac{T_1\left[\left(\frac{T_5}{T_1} - 1\right)\right]}{T_2\left[\left(\frac{T_3}{T_2} - 1\right) + k\frac{T_3}{T_2}\left(\frac{T_4}{T_3} - 1\right)\right]}$



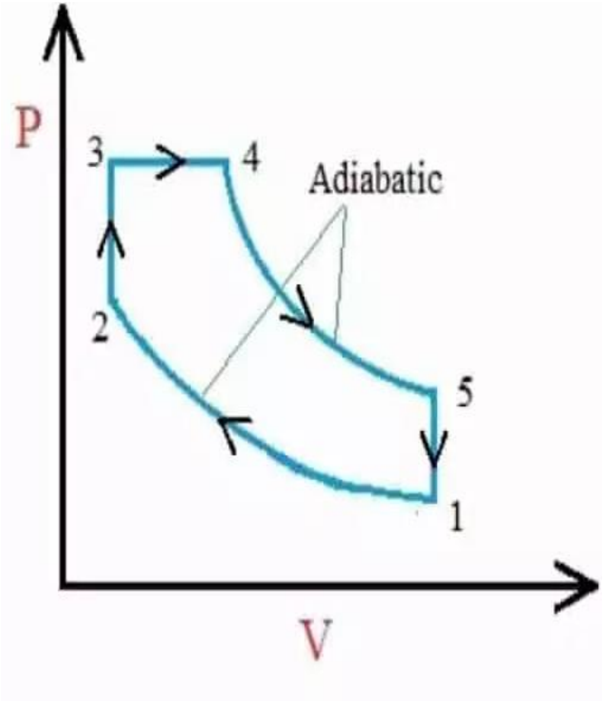
Dual Cycle

- $\eta_{dual} = 1 - \frac{T_1\left[\left(\frac{T_5}{T_4}\times\frac{T_4}{T_3}\times\frac{T_3}{T_2}\times\frac{T_2}{T_1}-1\right)\right]}{T_2\left[\left(\frac{T_3}{T_2}-1\right)+k\frac{T_3}{T_2}\left(\frac{T_4}{T_3}-1\right)\right]}$;

- $\eta_{dual} = 1 - \frac{1 \quad \left[\left(\frac{T_5}{T_4}\times\frac{T_4}{T_3}\times\frac{T_3}{T_2}\times\frac{T_2}{T_1}-1\right)\right]}{(r)^{k-1}\left[\left(\frac{T_3}{T_2}-1\right)+k\frac{T_3}{T_2}\left(\frac{T_4}{T_3}-1\right)\right]}$

- $\eta_{dual} = 1 - \frac{1 \quad \left[\left(\left(\frac{r_c}{r}\right)^{k-1}\times r_c\times r_p\times(r)^{k-1}-1\right)\right]}{(r)^{k-1}\left[(r_p-1)+kr_p(r_c-1)\right]}$

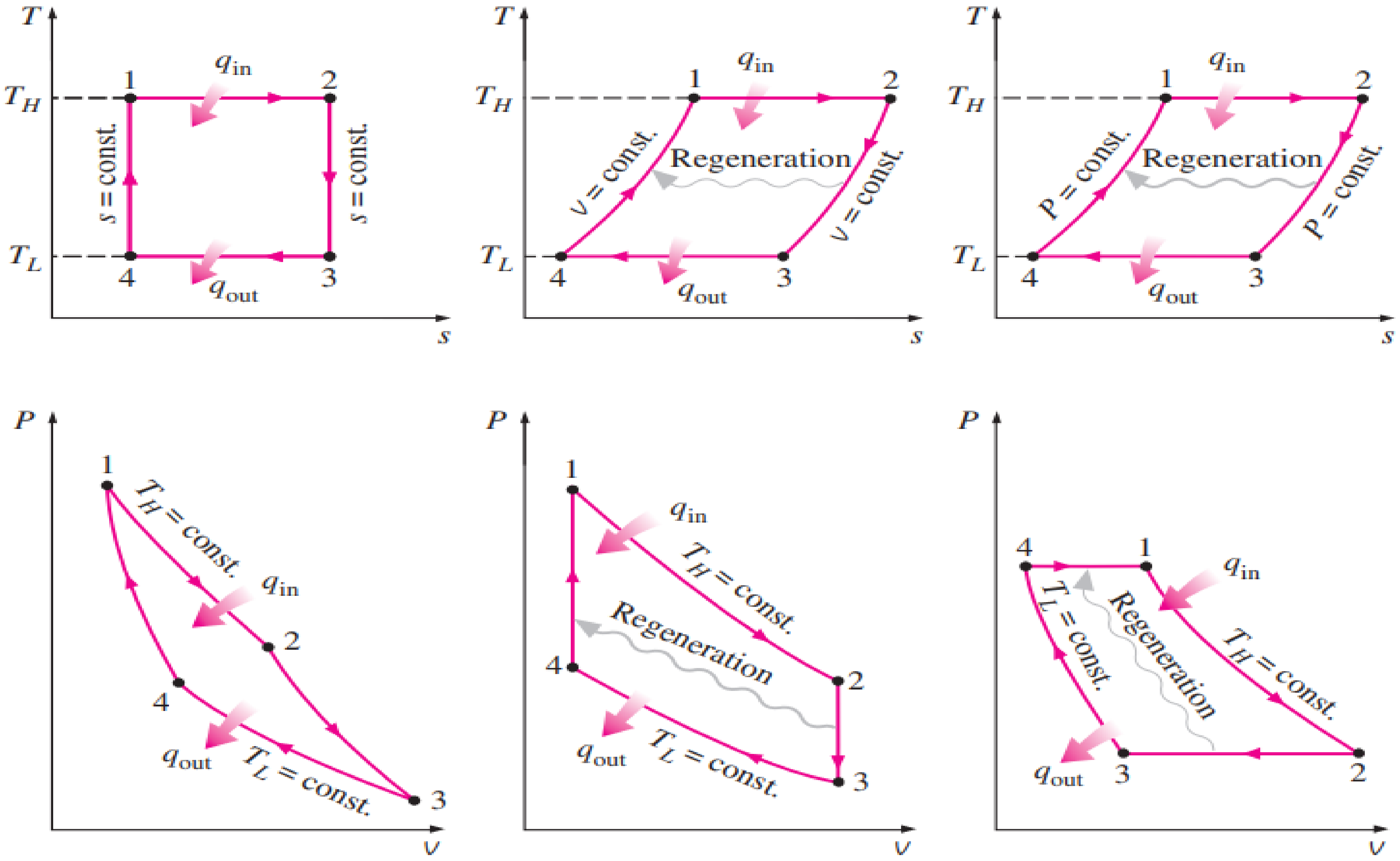
- $\boldsymbol{\eta_{dual} = 1 - \frac{1 \quad \left[\left(r_p\times {r_c}^{k}-1\right)\right]}{(r)^{k-1}\left[(r_p-1)+kr_p(r_c-1)\right]}}$



Stirling and Ericsson Cycles

- Otto and Diesel Cycles are composed entirely of internally reversible processes and thus are internally reversible cycles.
- However, these cycles are not totally reversible, since they involve heat transfer through a finite temperature difference during the non-isothermal heat-addition and heat-rejection processes.
- Therefore, the thermal efficiency of an Otto or Diesel engine will be less than that of a Carnot engine operating between the same temperature limits

- Two other cycles that involve an isothermal heat-addition process at TH and an isothermal heat-rejection process at TL
- Stirling cycle and the Ericsson cycle.
- Two isentropic processes in Carnot cycle in these cycles are replaced by two constant-volume regeneration processes in the Stirling cycle and by two constant-pressure regeneration processes in the Ericsson cycle.

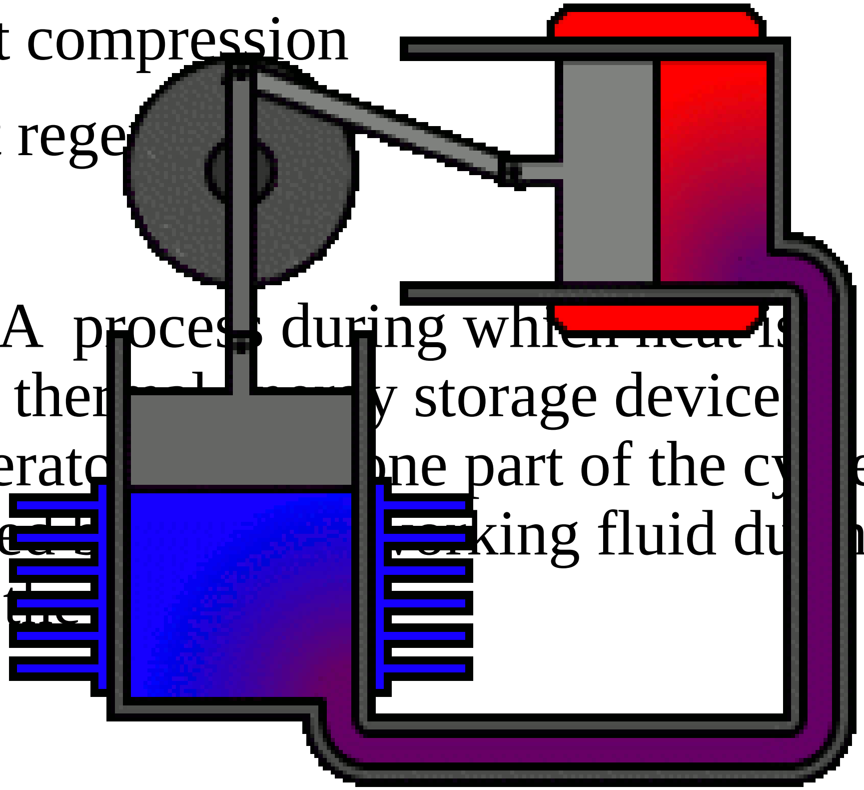


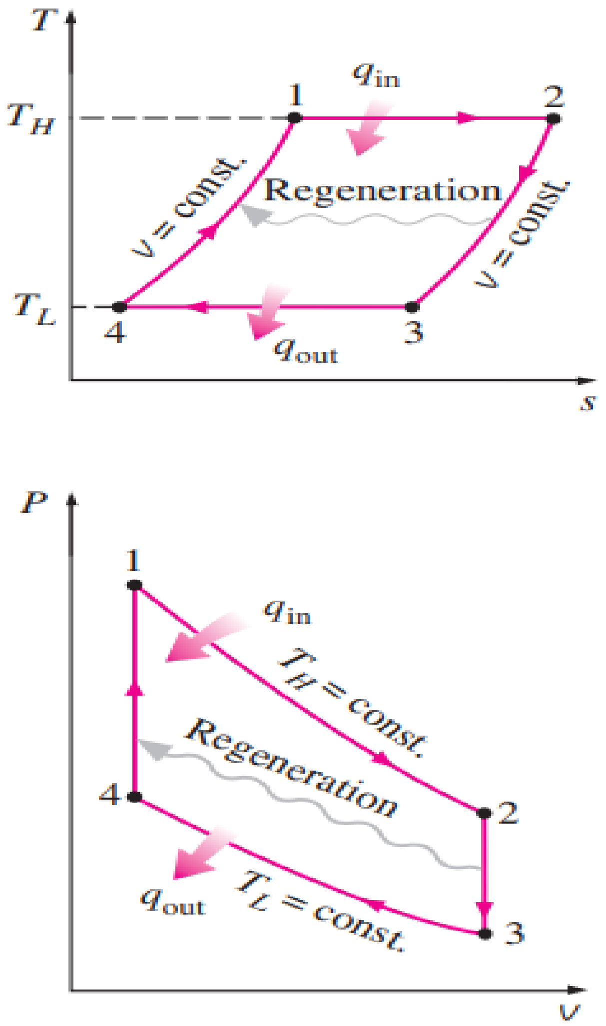
(*a*) Carnot cycle (*b*) Stirling cycle (*c*) Ericsson cycle

Stirling Cycle

- 1-2 T constant expansion
- 2-3 V constant regeneration
- 3-4 T constant compression
- 4-1 V constant rege

- Regeneration : A proces during which heat is transferred to a ther y storage device (called a regenerat ne part of the cy e and is transferred working fluid du ng another part of





(b) Stirling cycle

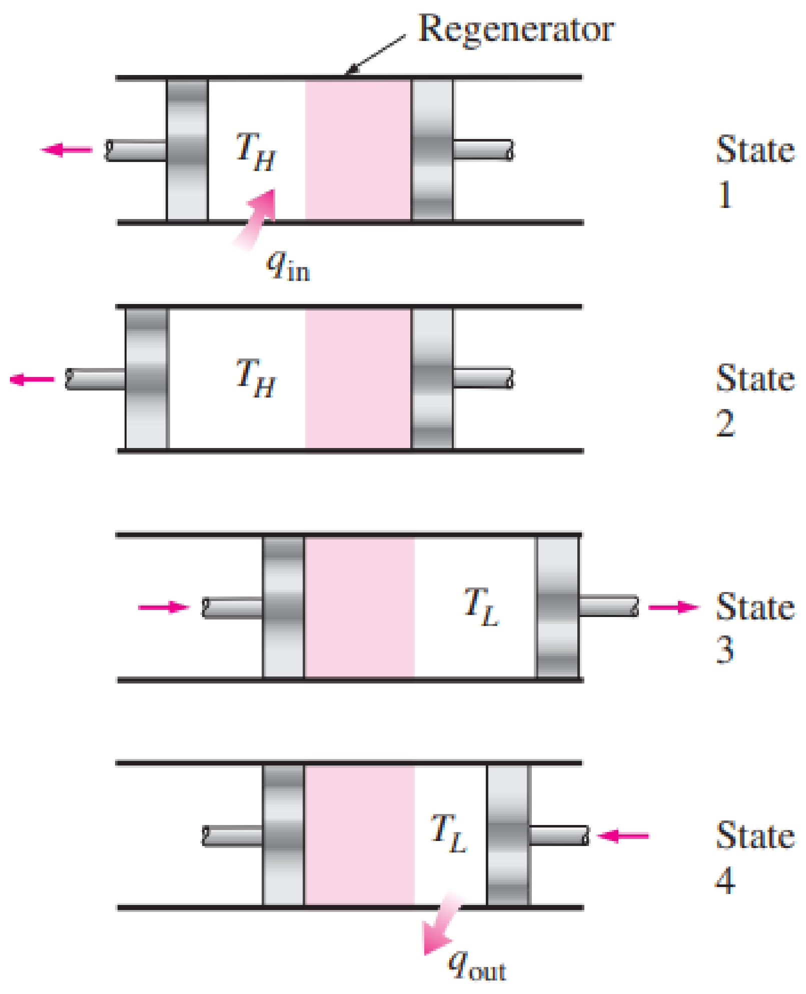
Stirling Cycle

- Robert Stirling : The execution of the Stirling cycle requires rather innovative hardware.

- This system consists of a cylinder with two pistons on each side and a regenerator in the middle.

- The regenerator can be a wire or a ceramic mesh or any kind of porous plug with a high thermal mass (mass times specific heat).

- It is used for the temporary storage of thermal energy. The mass of the working fluid contained within the regenerator at any instant is considered negligible.



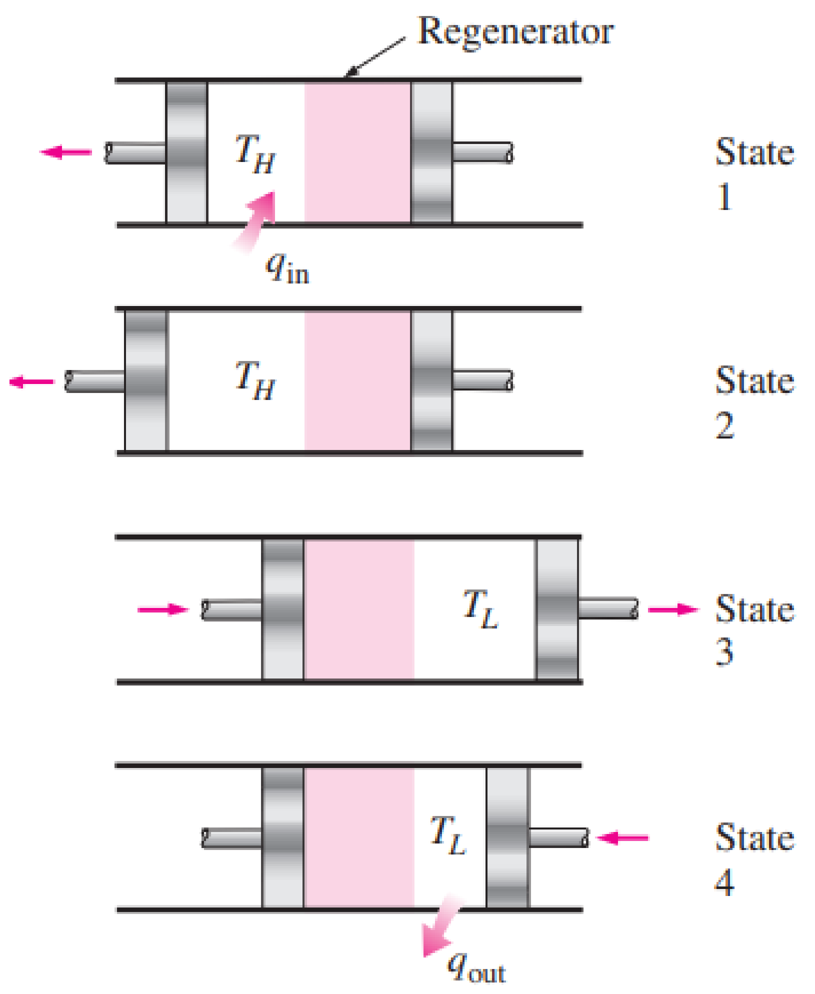
Stirling Cycle

- Initially, the left chamber houses the entire working fluid (a gas), which is at a high T and P

- During process 1-2, heat is transferred to the gas at T_H from a source at T_H. As the gas expands isothermally, the left piston moves outward, doing work, and the gas pressure drops.

- During process 2-3, both pistons are moved to the right at the same rate (to keep the volume constant) until the entire gas is forced into the right chamber.

- As the gas passes through the regenerator, heat is transferred to the regenerator and the gas temperature drops from T_H to T_L.



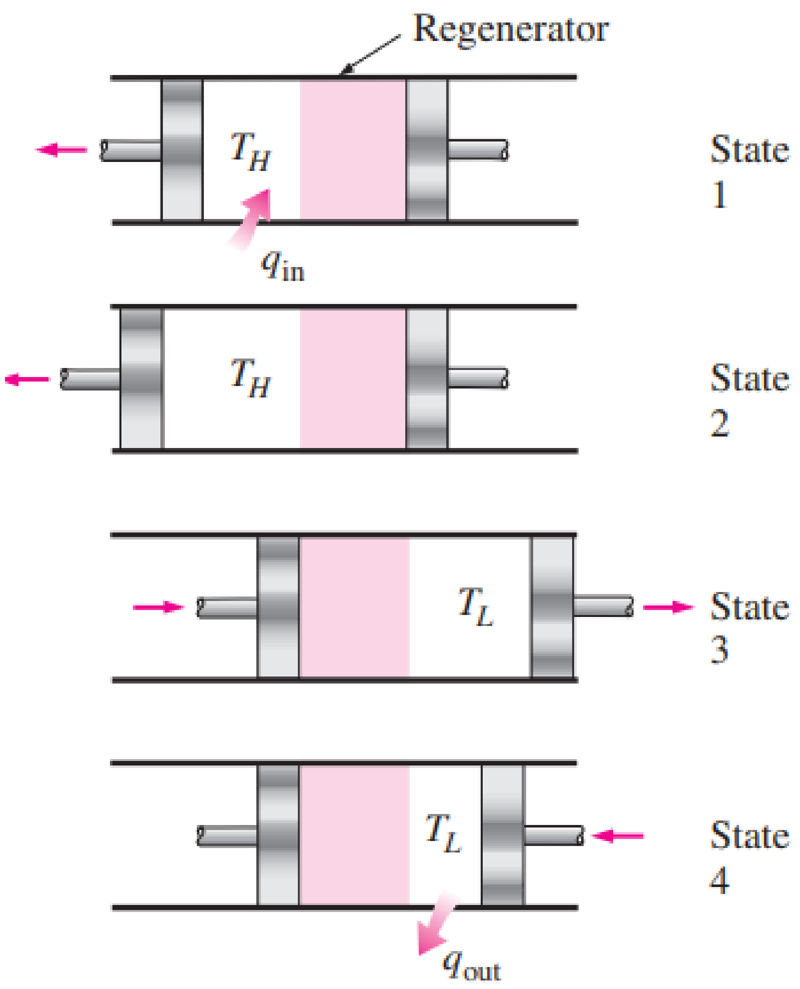
Stirling Cycle

- The temperature of the regenerator is T_H at the left end and T_L at the right end of the regenerator – state 3

- During process 3-4, the right piston is moved inward, compressing the gas. Heat is transferred from the gas to a sink at temperature T_L so that the gas temperature remains constant at T_L while the pressure rises.

- During process 4-1, both pistons move to the left at the same rate (to keep the volume constant), forcing the entire gas into the left chamber.

- The gas temperature rises from T_L to T_H as it passes through the regenerator and picks up the thermal energy stored there during process 2-3.

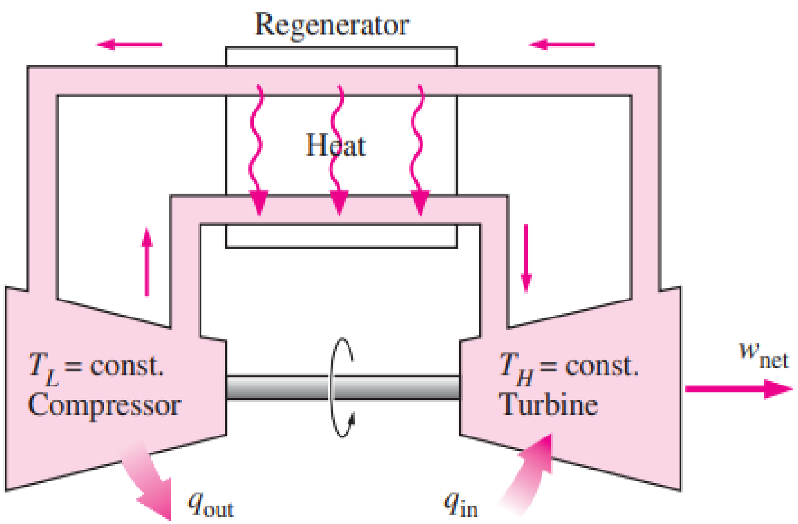


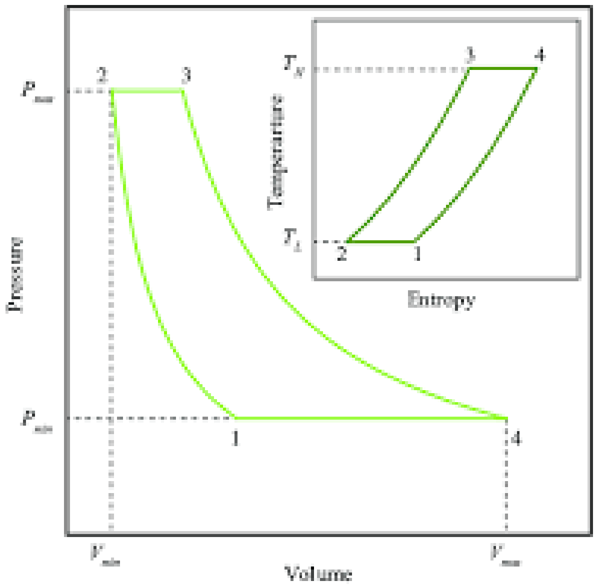
Ericsson Cycle

- Ericsson cycle is very much like the Stirling cycle but the two constant-volume processes are replaced by two constant-pressure processes.

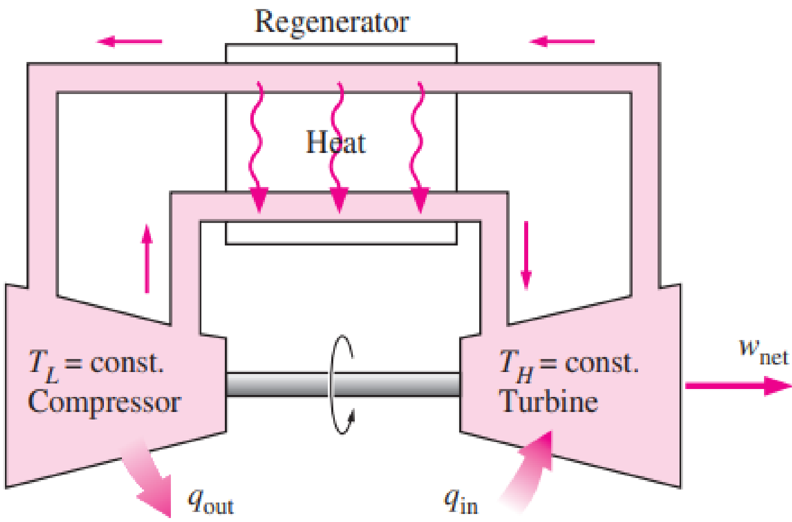
- Here the isothermal expansion and compression processes are executed in a compressor and a turbine, respectively, and a counter-flow heat exchanger serves as a regenerator.

- Hot and cold fluid streams enter the heat exchanger from opposite ends, and heat transfer takes place between the two streams. In the ideal case, the temperature difference between the two fluid streams does not exceed a differential amount at any point.



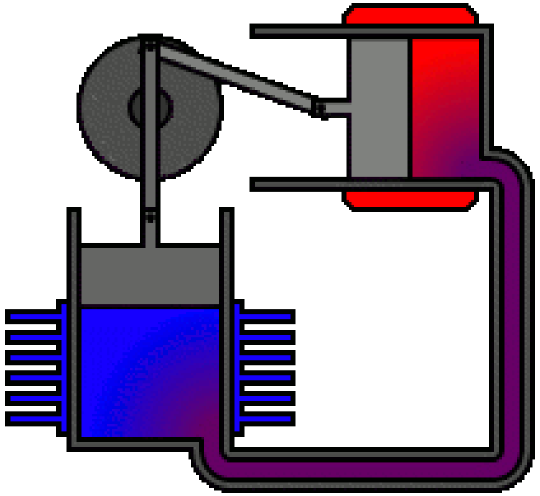


Stirling and Ericsson Cycle



- Both the Stirling and Ericsson cycles are totally reversible, as is the Carnot cycle, and thus according to the Carnot principle, all three cycles must have the same thermal efficiency when operating between the same temperature limits:

$$\eta_{th,Stirling} = \eta_{th,Ericsson} = \eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$

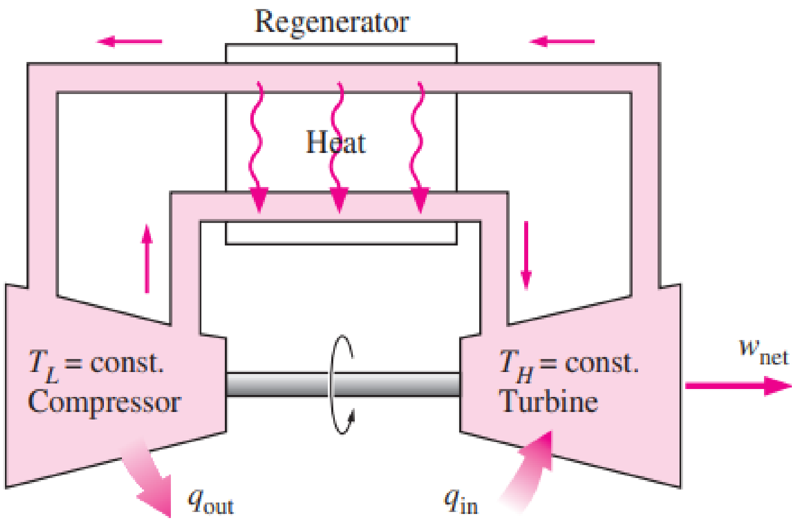


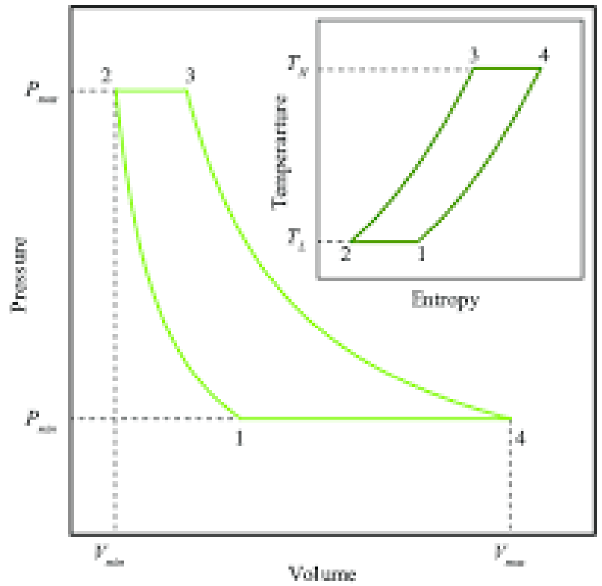
- These cycles are difficult to achieve in practice because they involve heat transfer through a differential temperature difference in all components.

- This would require providing infinitely large surface areas for heat transfer or allowing an infinitely long time for the process. - remained only theoretical interest in these cycles

Stirling and Ericsson Cycle

- However, there is renewed interest in engines that operate on these cycles because of their potential for higher efficiency and better emission control.
- The Ford Motor Company, General Motors Corporation, and the Phillips Research Laboratories of the Netherlands have successfully developed Stirling engines suitable for trucks, buses, and even automobiles.
- More research and development are needed before these engines can compete with the gasoline or diesel engines
- Stirling and the Ericsson engines are external combustion engines.





Stirling and Ericsson Cycle

- External combustion offers several advantages :

1) Variety of fuels can be used as a source of thermal energy.

2) There is more time for combustion, and thus the combustion process is more complete - less air pollution and more energy extraction from the fuel.

3) Closed cycle with a desirable working fluid. (stable, chemically inert, high thermal conductivity)

4) Normally, Hydrogen and Helium are two gases commonly employed in these engines.