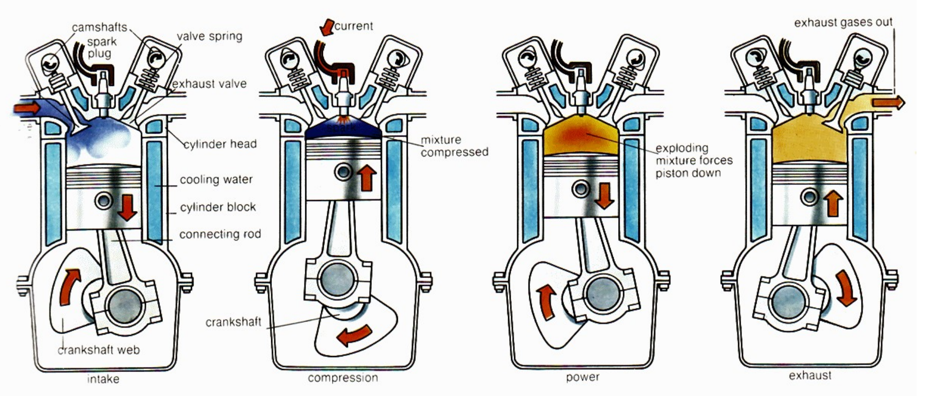
Lecture-10

Air Standard Cycles

Date- 30/8/2017, Wednesday

Introduction of Ideal Air Standard Power Cycles

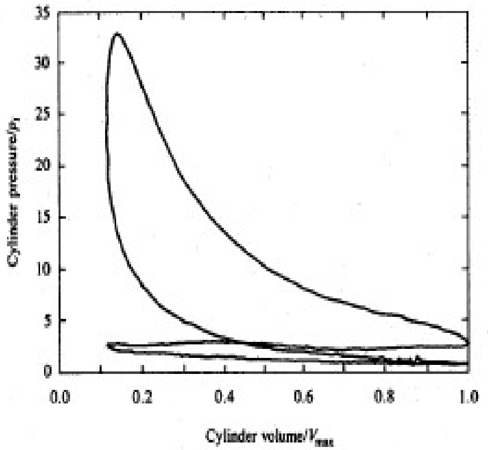
- The operating cycle of an internal combustion engine can be broken down into a sequence of separate processes: intake, compression & combustion, expansion, and exhaust.

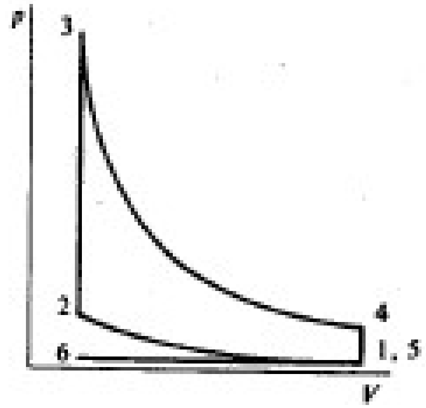


- With models for each of these processes, a simulation of a complete engine cycle can be built up which can be analyzed to provide information on engine performance.
- These model cycles are called air standard cycles.
- In an air standard cycles, a certain mass of air operates in a complete thermodynamic cycle, where heat is added or rejected with external heat reservoirs and all the process in the cycle is reversible.
- The three air standard cycles that model the IC engines are:
  - ✓ Otto cycle (approximation of SI engine)
  - ✓ Diesel cycle (approximation of CI engine)
  - ✓ Limited pressure cycle or Mixed cycle or Dual cycle

Difference between Air Standard Cycles and IC Engine Cycle

Actual SI Engine Cycle

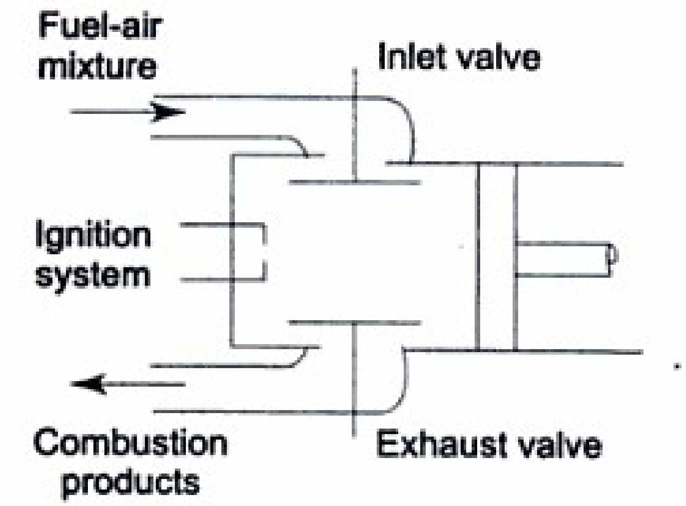




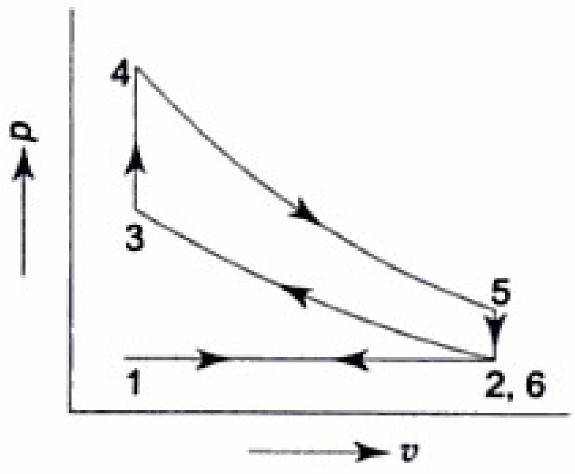
Air Standard Otto Cycle

- ❖ The processes of internal combustion engine is not reversible, where as air standard cycle processes are reversible.
- ❖ In internal combustion engine air-fuel mixture act as the working fluid. In air standard cycle air is considered to be the working fluid, with assumption of ideal gas.
- ❖ In internal combustion engine the individual processes can't be distinctly identifiable, they always overlap. In air standard cycle the processes are distinctly identifiable with no overlap.
- ❖ In internal combustion engine the working fluid's specific heat changes with pressure and temperature, where as in air standard cycle it is assumed that air's specific heat remain constant.

Otto Cycle

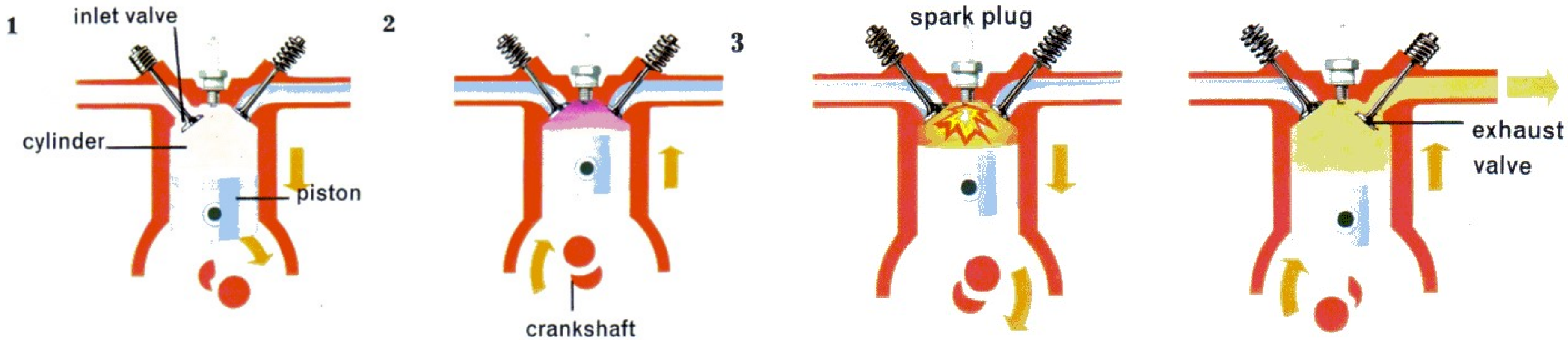


An ideal SI Engine



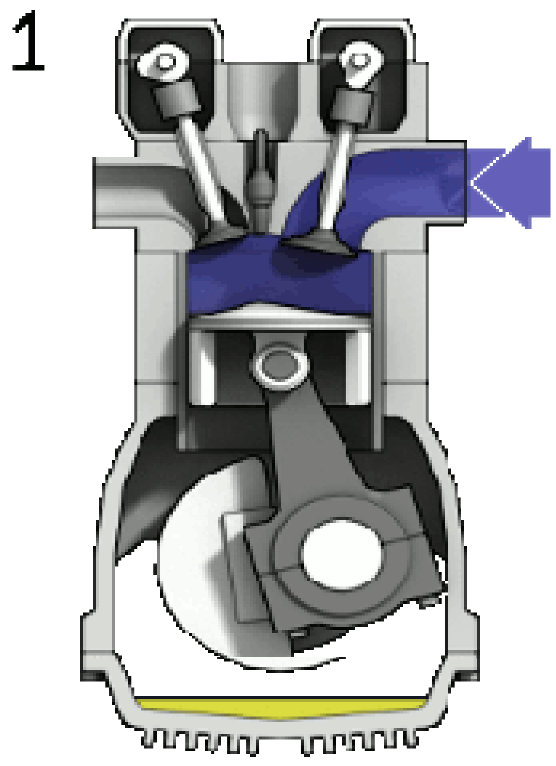
Indicator Diagram

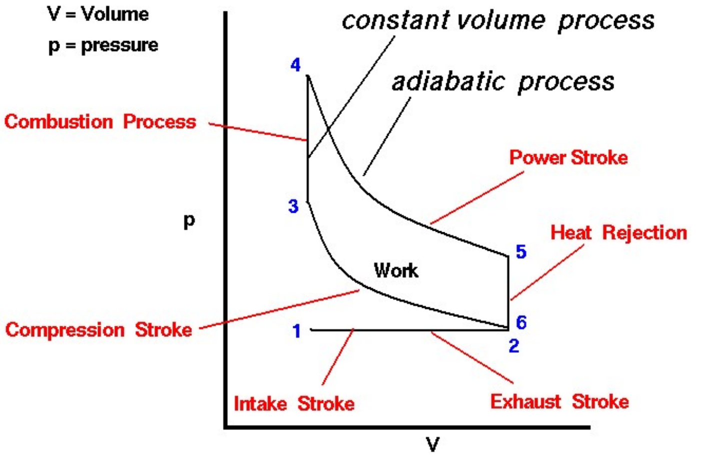
- ❖ Otto cycle is the air standard cycle for SI engine.
- ❖ This cycle contains two reversible adiabatic (constant entropy) and two reversible isochors (constant volume).



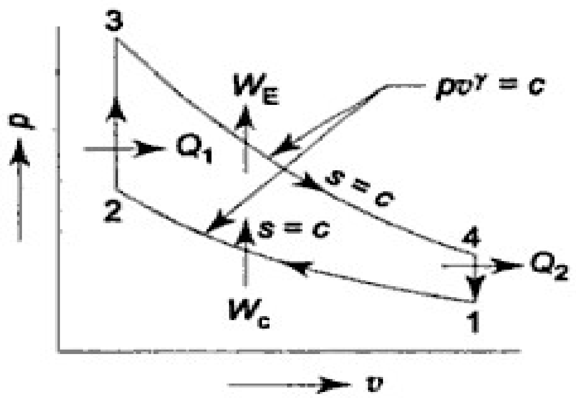
Otto Cycle

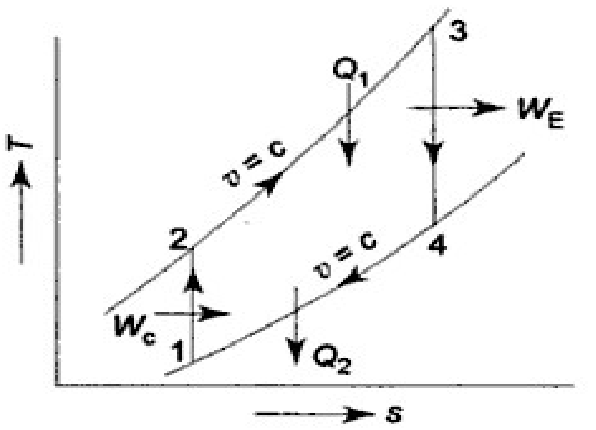
- **Process 1-2 - Intake:** The inlet valve is open, the piston moves to the right, admitting fuel-air mixture into the cylinder at constant pressure.
- **Process 2-3 - Compression:** Both the valves are closed, the piston compresses the combustible mixture to the minimum volume.
- **Process 3-4 – Combustion:** The mixture is then ignited by means of a spark, combustion takes place and there is an increase in temperature and pressure.
- **Process 4-5 – Expansion:** The product of combustion do work on the piston which moves to the right, and the pressure and temperature of the gas decrease.
- **Process 5-6 – Blow down:** The exhaust vale opens and the pressure drops to the initial pressure.
- **Process 6-1 – Exhaust:** With the exhaust valve open, the piston moves inwards to expel the combustion products from the cylinder at constant pressure.





Otto Cycle





p-v diagram of Otto cycle

T-S diagram of Otto cycle

- Air is compressed in process 1-2 reversibly and adiabatically ,
- Heat is added in to air at reversibly constant volume process 2-3,
- Work is done by air reversibly and adiabatically in process 3-4,
- Heat is rejected reversibly constant volume process 4-1 and the system comes back to initial state,
- If m is the fixed mass of air undergoing the cycle of operation then,

Heat supplied $Q_1=Q_{2-3}=mc_v(T_3-T_2)$

Heat rejected $Q_2=Q_{4-1}=mc_v(T_4-T_1)$

Efficiency can be given as;

$$\boxed{\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_3 - T_2)}{mc_v(T_4 - T_1)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}}$$

Otto Cycle

- From process 1-2:

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$$

- From process 3-4:

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$$

- From above equations,

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \Rightarrow \frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1}$$

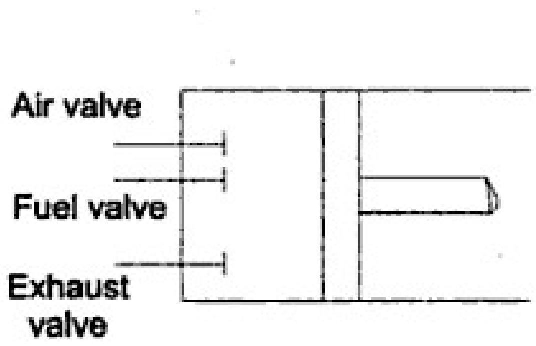
- Using above expressions, efficiency can be given as;

$$\boxed{\eta = 1 - \left(\frac{v_2}{v_1}\right)^{\gamma-1} = 1 - \frac{1}{r_c^{\gamma-1}}}$$

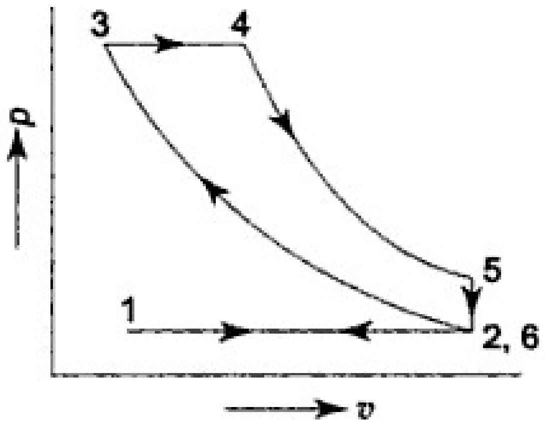
where r_c is the compression ratio, $r_c = v_1/v_2$

- Thus the efficiency of air standard Otto cycle is a function of compression ratio only. The higher the compression ratio the higher the efficiency.
- The compression ratio can not be increased beyond a certain limit because of noisy and destructive combustion phenomenon detonation.

Diesel Cycle

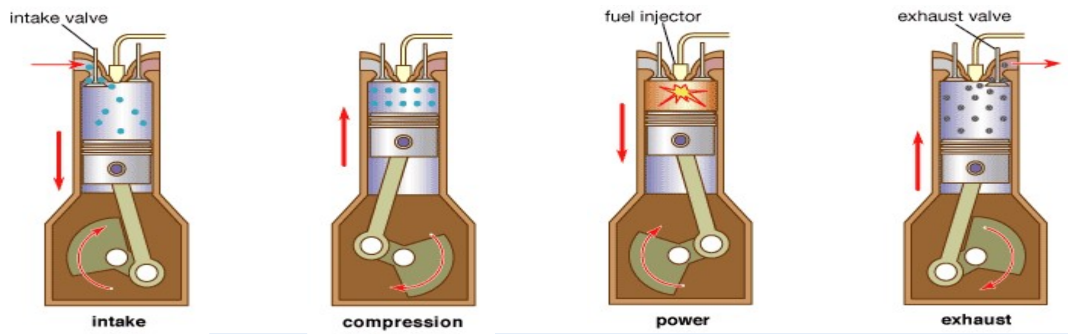


An ideal CI Engine



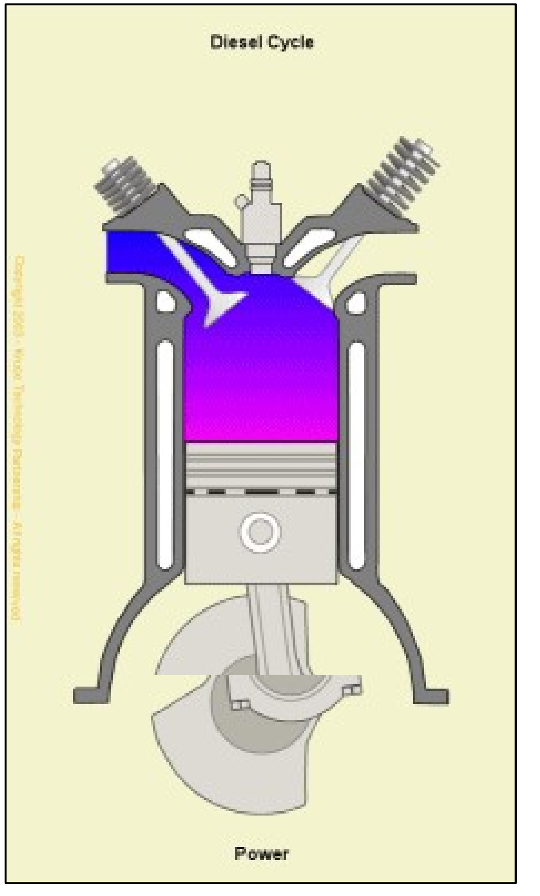
Indicator Diagram

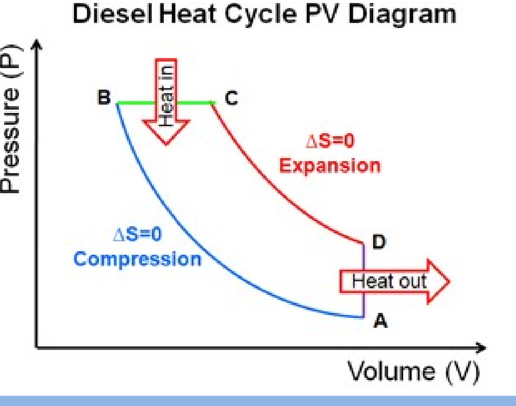
- ❖ Diesel engine is the air standard cycle for CI engine.
- ❖ Limitation of compression ratio of SI engine can be overcome by compressing air alone, instead of fuel air mixture, then injecting the fuel into the cylinder in spray form when combustion is desired.
- ❖ Temperature of the air after compression must be high enough so that fuel sprayed into the hot air burns spontaneously.
- ❖ Diesel cycle contains 2 reversible adiabatic, 1 reversible isobar and 1 reversible isochors process.



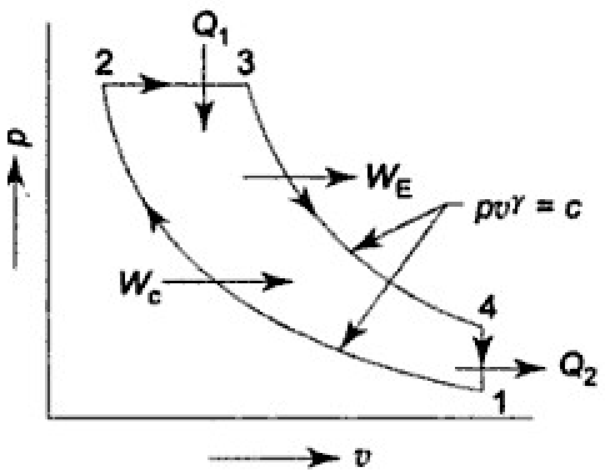
Diesel Cycle

- **Process 1-2 – Intake:** The air valve is open. The piston moves out admitting air into the cylinder at constant pressure
- **Process 2-3 – Compression:** The air is then compressed by the piston to the minimum volume with all valve closed
- **Process 3-4 – Fuel injection and combustion:** The fuel valve is open, fuel is sprayed over the hot air, and combustion takes place at constant pressure
- **Process 4-5 – Expansion:** The combustion products expand, doing work on the piston which moves out to the maximum volume
- **Process 5-6 – Blow-down:** The exhaust valve opens, and the pressure drops to initial pressure
- **Process 6-1 – Exhaust:** With the exhaust valve open, the piston moves towards the cylinder cover driving away the combustion products from the cylinder at constant pressure.

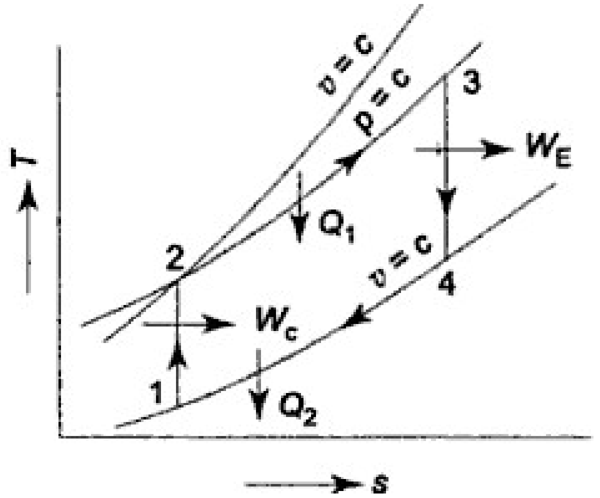




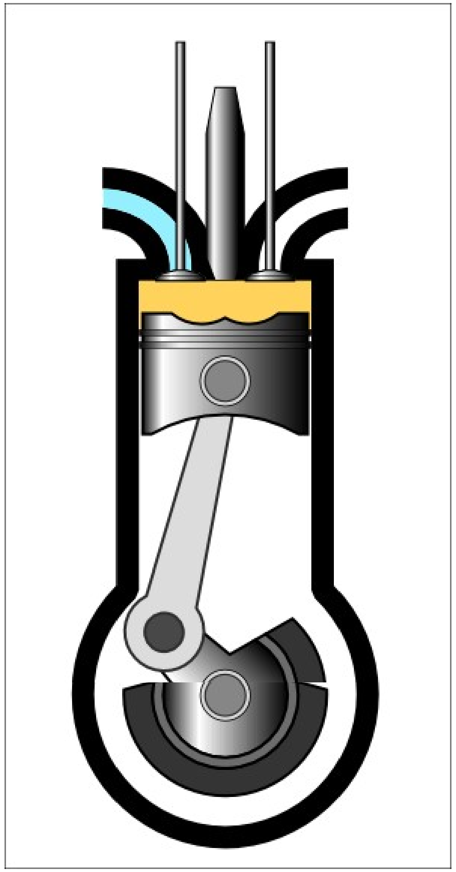
Diesel Cycle



p-v diagram of Diesel cycle



T-S diagram of Diesel cycle



- ❖ Air is compressed in process 1-2 reversibly and adiabatically ,
- ❖ Heat is added in to air at reversibly constant pressure process 2-3,
- ❖ Work is done by air reversibly and adiabatically in process 3-4,
- ❖ Heat is rejected reversibly constant volume process 4-1 and the cycle repeat,
- ❖ If m is the fixed mass of air undergoing the cycle of operation then,

Heat supplied $Q_1 = Q_{2\text{-}3} = mc_p(T_3 - T_2)$, Heat rejected $Q_2 = Q_{4\text{-}1} = mc_v(T_4 - T_1)$

Efficiency can be given as;

$$\boxed{\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_3 - T_2)}{mc_p(T_4 - T_1)} = 1 - \frac{T_4 - T_1}{\gamma(T_3 - T_2)}}$$

Diesel Cycle

❖ Compression ratio $r_c = \dfrac{v_1}{v_2}$

❖ Cut-off ratio $r_k = \dfrac{v_3}{v_2}$

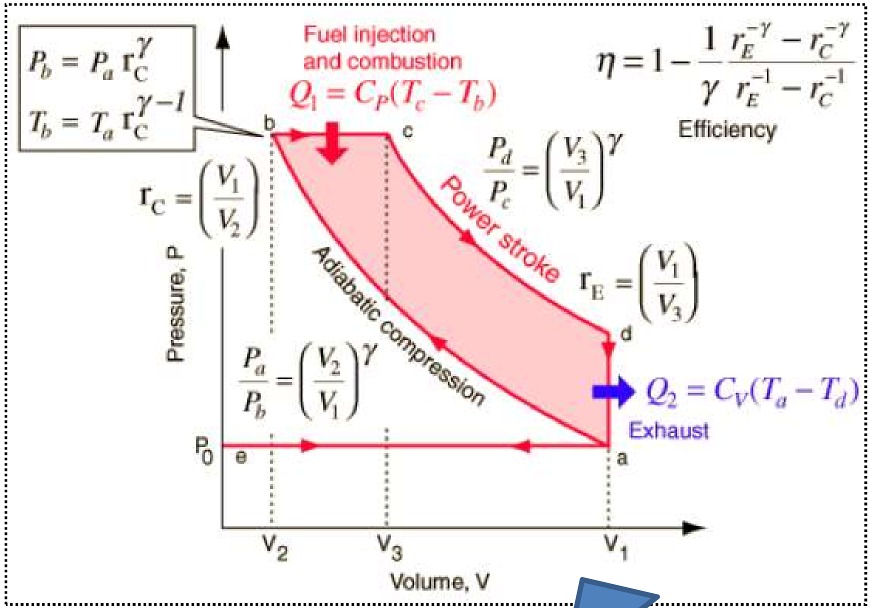
❖ Expansion ratio $r_e = \dfrac{v_4}{v_3}$ and $r_c = r_e r_k$

❖ From Process 3-4 $\dfrac{T_4}{T_3} = \left(\dfrac{v_3}{v_4}\right)^{\gamma-1} = \dfrac{1}{r_e^{\gamma-1}} \Rightarrow T_4 = T_3 \dfrac{r_k^{\gamma-1}}{r_c^{\gamma-1}}$

❖ From process 2-3 $\dfrac{T_2}{T_3} = \dfrac{p_2 v_2}{p_3 v_3} = \dfrac{v_2}{v_3} = \dfrac{1}{r_k} \Rightarrow T_2 = T_3 \dfrac{1}{r_k}$

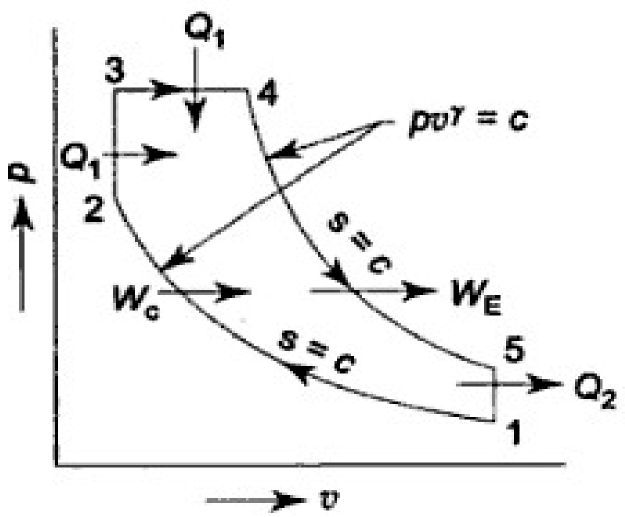
❖ From process 1-2 $\dfrac{T_1}{T_2} = \left(\dfrac{v_2}{v_1}\right)^{\gamma-1} = \dfrac{1}{r_c^{\gamma-1}} \Rightarrow T_1 = T_2 \dfrac{1}{r_c^{\gamma-1}} = \dfrac{T_3}{r_k} \dfrac{1}{r_c^{\gamma-1}}$

❖ With help of above equations, $\boxed{\eta = 1 - \dfrac{1}{\gamma} \cdot \dfrac{1}{r_c^{\gamma-1}} \cdot \dfrac{r_k^{\gamma} - 1}{r_k - 1}}$

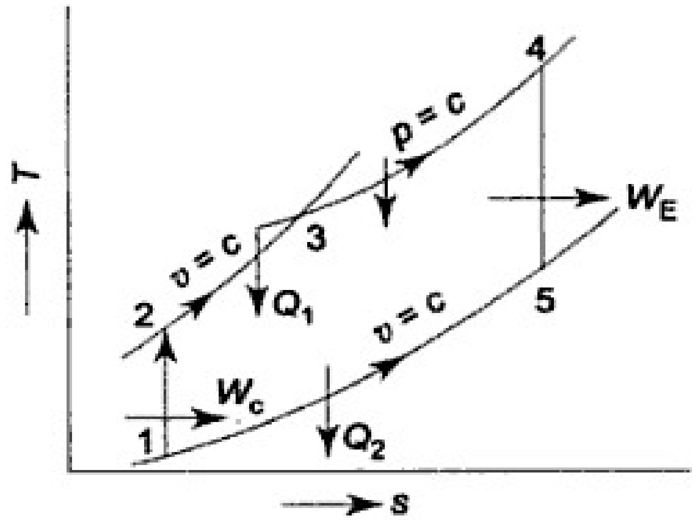


❖ As $r_k > 1$ the $\dfrac{1}{\gamma} \cdot \dfrac{r_k^{\gamma} - 1}{r_k - 1}$ is also greater than unity. Therefore the efficiency of Diesel cycle is less than Otto cycle for same compression ratio.

Limited Pressure Cycle, Mixed Cycle or Dual Cycle



p-v diagram of Dual cycle



T-S diagram of Dual cycle

- ❖ The air standard diesel cycle does not simulate exactly the pressure volume variation in an actual CI engine, where the fuel injection is started before the end of the compression stroke.
- ❖ A closer approximation to CI engine is Dual cycle, in which some part of the heat is added to air at constant volume and remainder at constant pressure.
- ❖ Dual cycle contains two reversible adiabatic, one reversible isobar and two reversible isochors process.

Dual Cycle

- Air is compressed in process 1-2 reversibly and adiabatically.
- Heat is added in to air at reversibly constant pressure process 2-3 and constant volume process 3-4.
- Work is done by air reversibly and adiabatically in process 4-5.
- Heat is rejected reversibly constant volume process 5-1 and the cycle repeat.
- If m is the fixed mass of air undergoing the cycle of operation then,

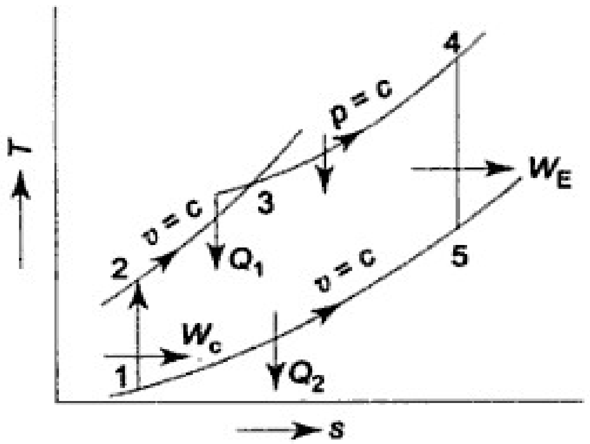
  Heat supplied $Q_1 = mc_v(T_3 - T_2) + mc_p(T_4 - T_3)$.

  Heat rejected $Q_2 = mc_v(T_5 - T_1)$

  Efficiency can be given as;

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_5 - T_1)}{mc_v(T_3 - T_2) + mc_p(T_4 - T_3)}$$

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



- Compression ratio $r_c = \frac{v_1}{v_2}$ Cut-off ratio $r_k = \frac{v_4}{v_3}$
- Expansion ratio $r_e = \frac{v_5}{v_4}$ and Const. volume pressure ratio $r_p = \frac{p_3}{p_2}$

$$r_c = r_e r_k$$

Dual Cycle

- From process 3-4,

$$r_k = \frac{v_4}{v_3} = \frac{T_4 p_3}{T_3 p_4} = \frac{T_4}{T_3} \Rightarrow T_3 = T_4 \frac{1}{r_k}$$

- From process 2-3,

$$\frac{p_2 v_2}{T_3} = \frac{p_3 v_3}{T_3} \Rightarrow T_2 = T_3 \frac{p_2}{p_3} = \frac{T_4}{r_p r_k}$$

- From process 1-2,

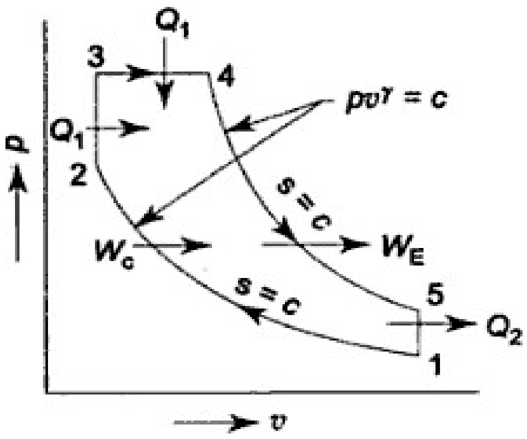
$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \frac{1}{r_c^{\gamma-1}} \Rightarrow T_1 = \frac{T_4}{r_p r_k r_c^{\gamma-1}}$$

- From process 4-5,

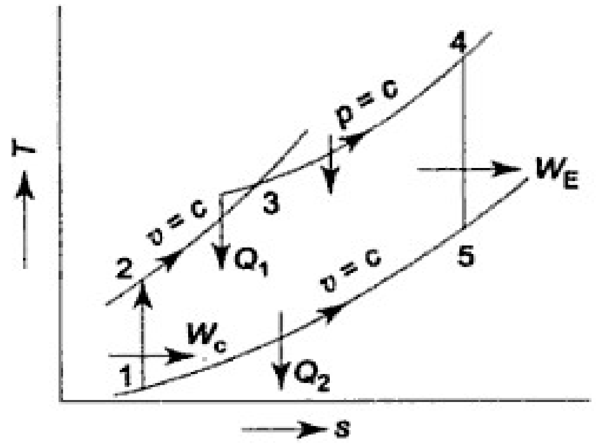
$$\frac{T_5}{T_4} = \left(\frac{v_4}{v_5}\right)^{\gamma-1} = \frac{1}{r_e^{\gamma-1}} \Rightarrow T_5 = T_4 \frac{r_k^{\gamma-1}}{r_c^{\gamma-1}}$$

- With help of above equations,

$$\boxed{\eta = 1 - \frac{1}{r_c^{\gamma-1}} \cdot \frac{r_p r_k^{\gamma} - 1}{r_p - 1 + \gamma r_p (r_k - 1)}}$$

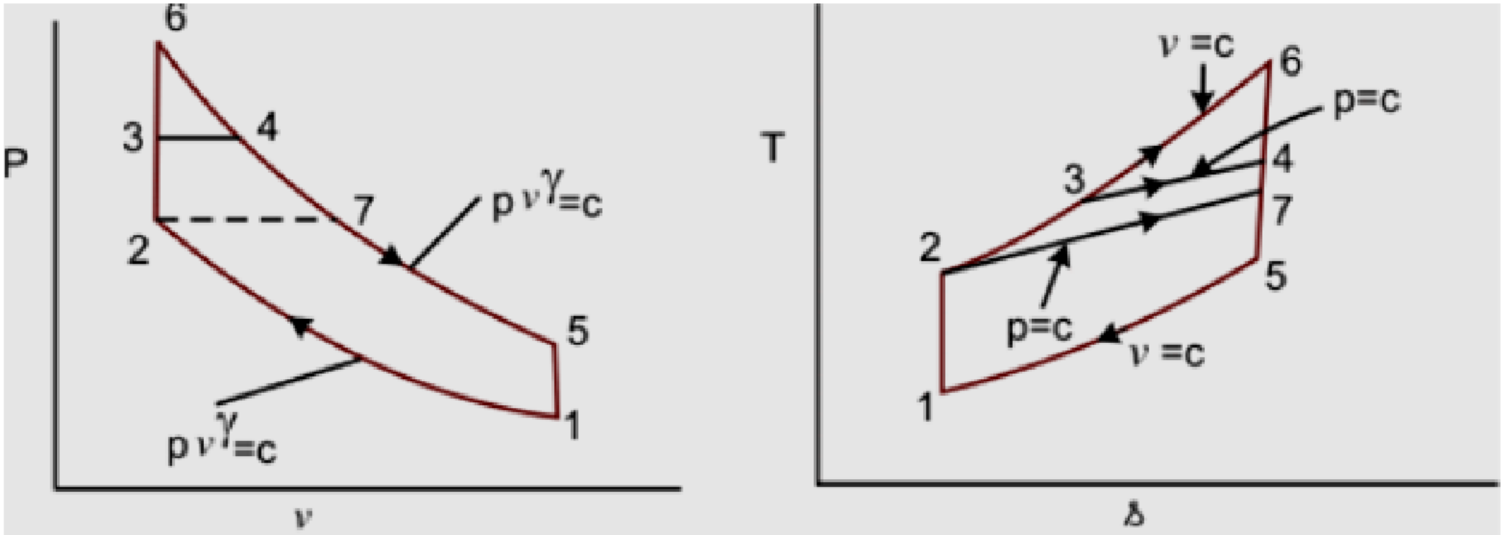


p-v diagram of Dual cycle



T-S diagram of Dual cycle

Comparison of Otto, Diesel and Dual Cycles



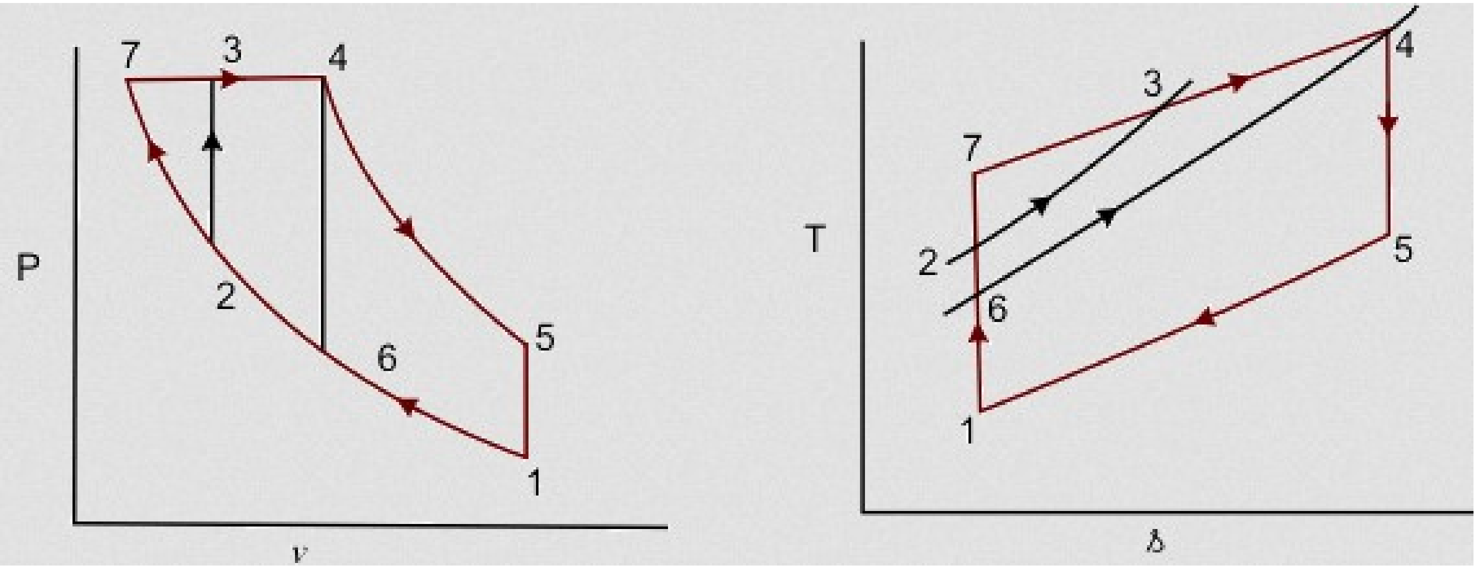
Otto, Diesel and Dual cycle for same comparison ratio

❖ **For same compression ratio**

- 1-2-6-5 → Otto cycle 1-2-7-5 → Diesel cycle and 1-2-3-4-5 → Dual cycle,
- For the same Q2 the higher the Q1, the higher is the cycle efficiency.
- In the T-S diagram the area under 2-6 represent Q1 for the Otto cycle, area under 2-7 represent Q1 for the Diesel cycle and area under 2-6 represent Q1 for the Dual cycle.
- From the diagram for same compression ratio;

$$\boxed{\eta_{otto} > \eta_{dual} > \eta_{diesel}}$$

Comparison of Otto, Diesel and Dual Cycles



Otto, Diesel and dual cycle for same maximum pressure and temperature

- **For same maximum pressure and temperature**
  - 1-6-4-5→Otto cycle, 1-7-4-5→Diesel cycle, 1-2-3-4-5 →Dual cycle,
  - Q1 represented by the area under 6-4 for Otto cycle, by the area under 7-4 for the diesel cycle and area under 2-3-4 for the Dual cycle. Q2 being the same for all.
  - From the diagram for same maximum pressure and temperature ,

$$\boxed{\eta_{diesel} > \eta_{dual} > \eta_{otto}}$$

Deviation of Actual Cycle from Air Standard Cycle

- The actual cycle deviates from the air standard cycles for following factors

Heat transfer

- Heat transfer from the burned gases have significant effect on the P-V line.
- Due to heat transfer during combustion, the pressure at the end of combustion in the real cycle will be lower.
- During expansion, heat transfer will cause the gas pressure in the real cycle to fall below an isentropic expansion line as the volume increases.
- A decrease in efficiency results from this heat loss.

Finite Combustion time

- Combustion typically starts 10 to 40 CAD before TDC, is half complete at about 10° after TDC, and is essentially complete 30° to 40° after TDC.
- Peak pressure occurs at about 15° after TDC . In a diesel engine, the burning process starts shortly before TDC.
- The pressure rises rapidly to a peak some 5° to 10° after TDC since the initial rate of burning is fast.
- However, the final stages of burning are much slower, and combustion continues until 40° to 50° after TDC.

Deviation of Actual Cycle from Air Standard Cycle

- Thus, the peak pressure in the engine is substantially below the fuel-air cycle peak pressure value, because combustion continues until well after TC, when the cylinder volume is much greater than the clearance volume.
- After peak pressure, expansion stroke pressures in the engine are higher than fuel-air cycle values in the absence of other loss mechanisms, because less work has been extracted from the cylinder gases.

Exhaust blow down loss

- In the real engine operating cycle, the exhaust valve is opened some 60° before BC to reduce the pressure during the first part of the exhaust stroke in four-stroke engines and to allow time for scavenging in two stroke engines.
- The gas pressure at the end of the expansion stroke is therefore reduced below the isentropic line.
- A decrease in expansion-stroke work transfer results.

Crevice effect and leakage

- As the cylinder pressure increases, gas flows into crevices such as the regions between the piston, piston rings, and cylinder wall.
- These crevice regions can comprise a few percent of the clearance volume.
- This flow reduces the mass in the volume above the piston crown, and this flow is cooled by heat transfer to the crevice walls.

Deviation of Actual Cycle from Air Standard Cycle

- In premixed charge engines, some of this gas is unburned and some of it will not burn.
- Though much of this gas returns to the cylinder later in the expansion, a fraction, from behind and between the piston rings, flows into the crankcase.
- All these effects reduce the cylinder pressure during the latter stages of compression, during combustion, and during expansion below the value that would result if crevice and leakage effects were absent.

Incomplete combustion

- Combustion of the cylinder charge is incomplete; the exhaust gases contain combustible species.
- In spark-ignition engines the hydrocarbon emissions from a warmed-up engine are 2 to 3 percent of the fuel mass under normal operating conditions.
- Carbon monoxide and hydrogen in the exhaust contain an additional 1 to 2 percent or more of the fuel energy, even with excess air present.
- Hence, the chemical energy of the fuel which is released in the actual engine is about 5 percent less than the chemical energy of the fuel inducted.
- In diesel engines, the combustion inefficiency is usually less, about 1 to 2 percent, so this effect is smaller.