2.Gas power Cycles

BITS Pilani
Dubai Campus

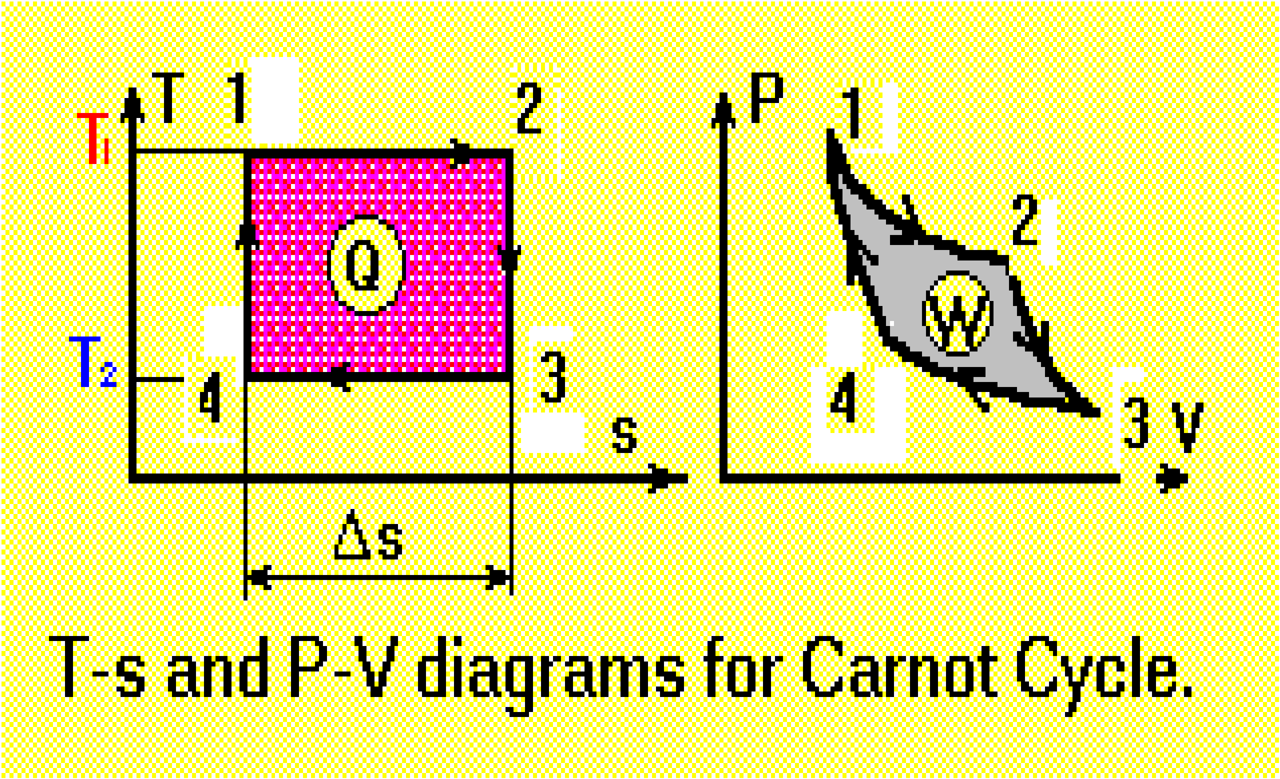
THE CARNOT CYCLE

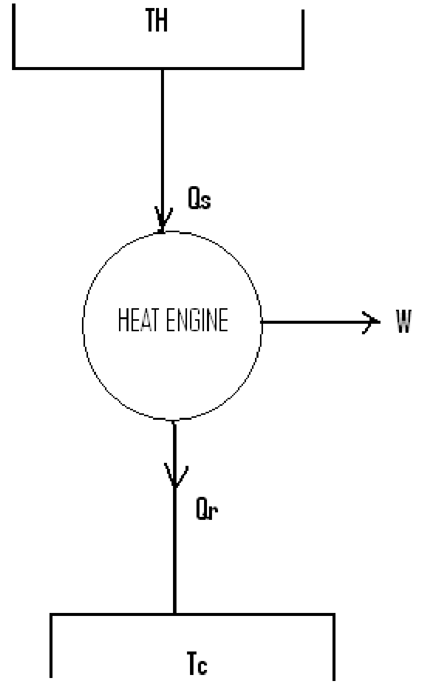
- Heat engine operates on a cycle.
- The efficiency of heat engine depends on how the individual processes are executed.
- The most efficient cycles are reversible cycles, that is, the processes that make up the cycle are all reversible processes.
- Reversible cycles cannot be achieved in practice. However, they provide the upper limits on the performance of real cycles.

- The fundamental thermodynamic cycle proposed by French engineer Sadi Carnot in 1824, in an attempt to explain the working of the steam engine.
- Carnot cycle is one of the best-known reversible cycles.
- The Carnot cycle is composed of four reversible processes.

CARNOT CYCLE

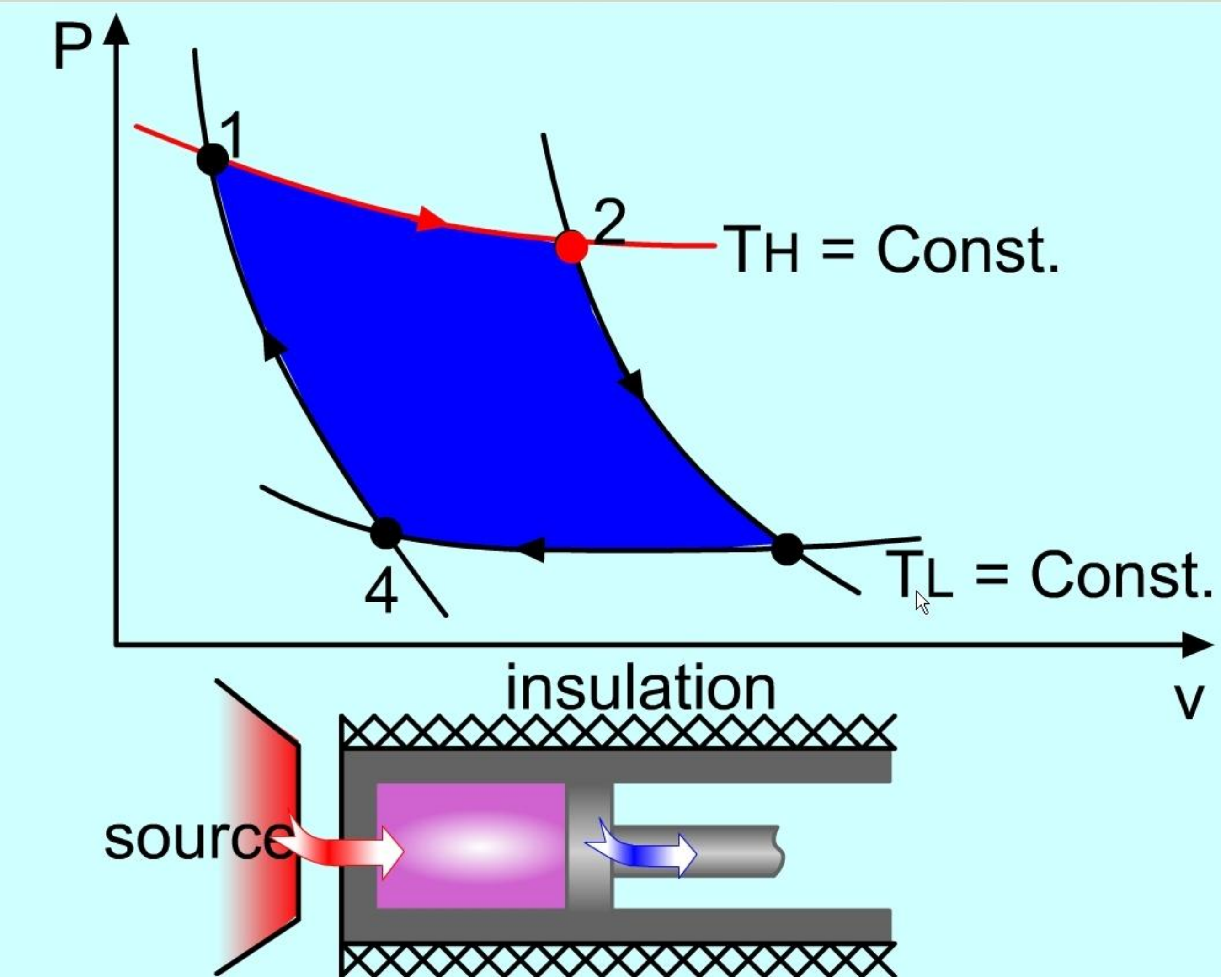
- Consider an adiabatic piston-cylinder device that contains gas.
- The four reversible processes that make up the Carnot cycle are as follows:
  - 1-2 Isothermal Expansions
  - 2-3 Adiabatic expansions,
  - 3-4 Isothermal compressions and
  - 4-1 Adiabatic compressions.



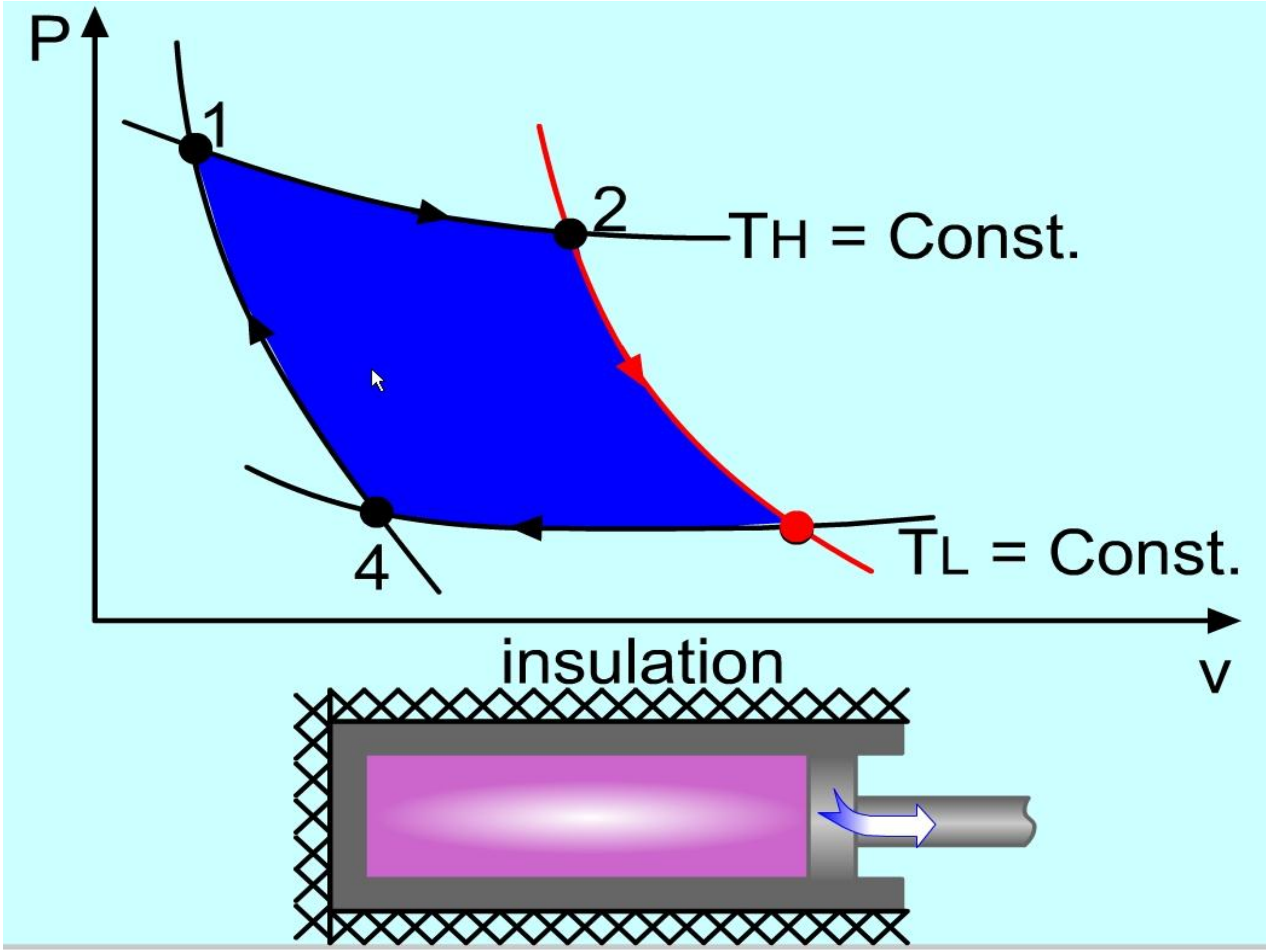


- **Figure** : A Carnot cycle acting as a heat engine, illustrated on a temperature-entropy diagram. The cycle takes place between a hot reservoir at temperature T_H and a cold reservoir at temperature T_C. The vertical axis is temperature, the horizontal axis is entropy.

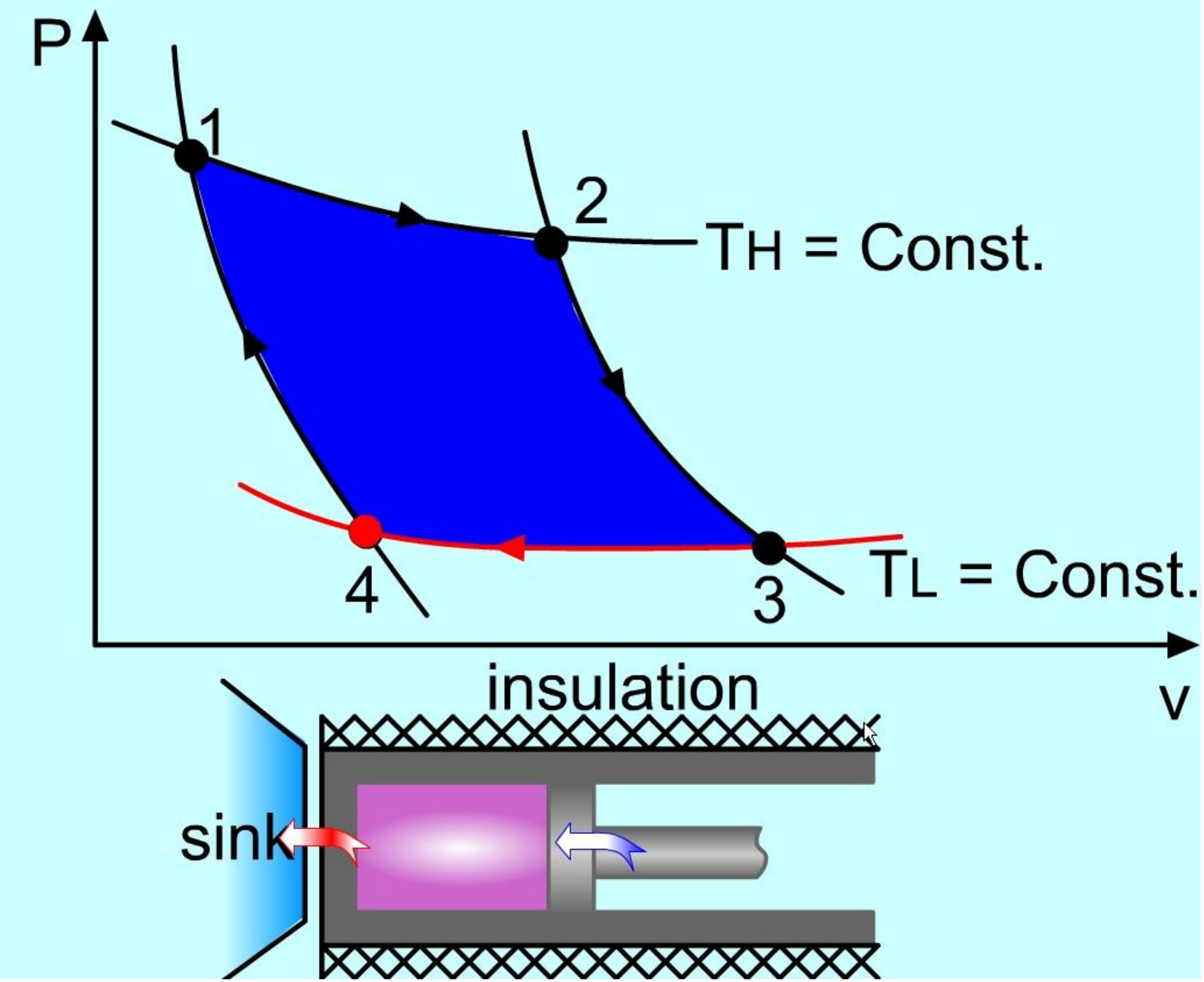
The Carnot Cycle (1-2): Reversible Isothermal Expansion



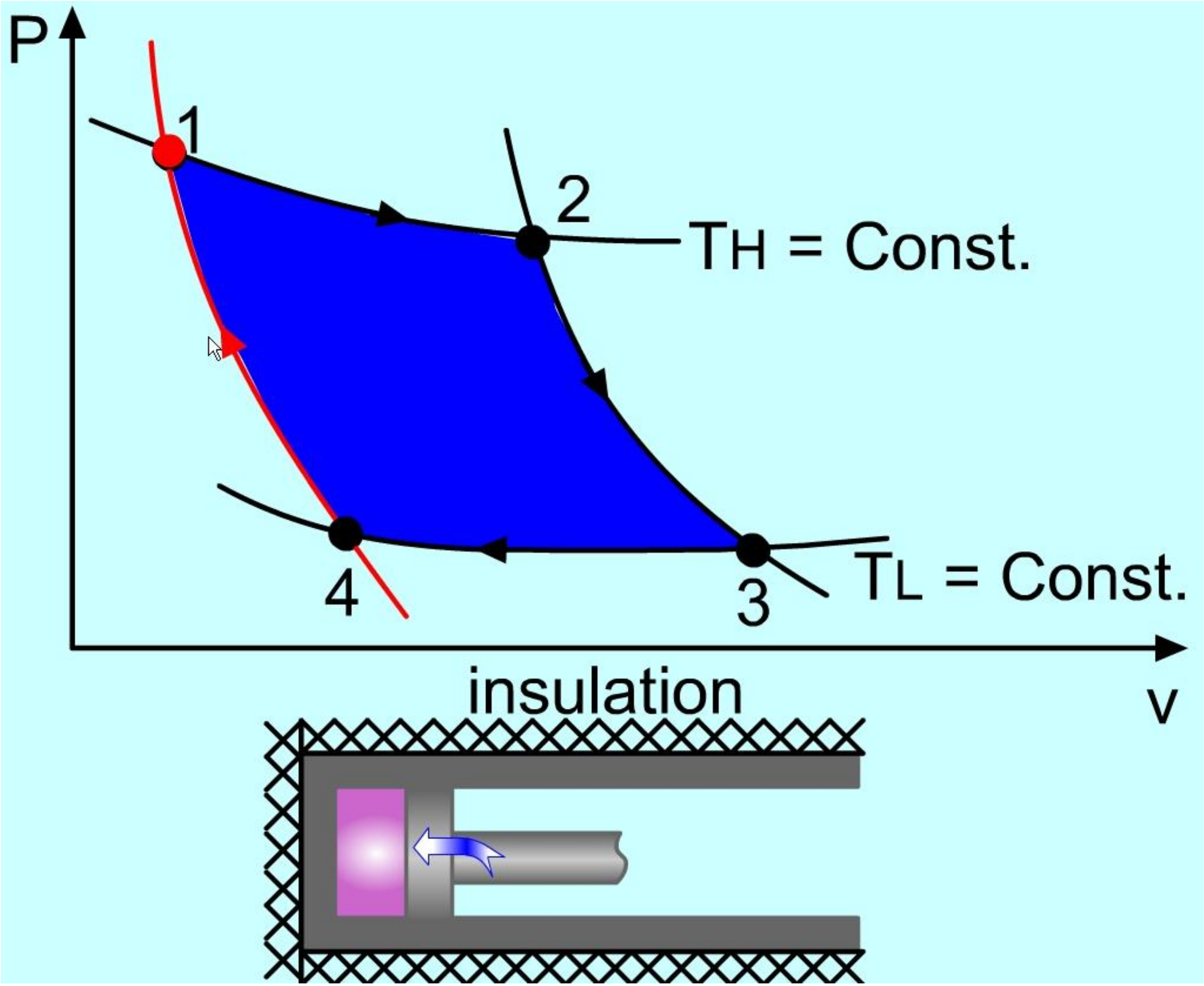
The Carnot Cycle (2-3): Reversible Adiabatic Expansion



The Carnot Cycle (3-4): Reversible Isothermal Compression



The Carnot Cycle (4-1): Reversible Adiabatic Compression



The Carnot principle

•The Carnot principle states that the reversible heat engines have the highest efficiencies when compared to irreversible heat engines working between the same two reservoirs.

• And the efficiencies of all reversible heat engines are the same if they work between the same two reservoirs.

- The efficiency of a reversible heat engine is independent
  - on the working fluid used and its properties,
  - The way the cycle operates,
  - The type of the heat engine.
- The efficiency of a reversible heat engine is a function of the reservoirs' temperature only.

BITS Pilani
Dubai Campus

innovate achieve lead

$$\eta_{th} = 1 - Q_L/Q_H = g(T_H,T_L)$$

or

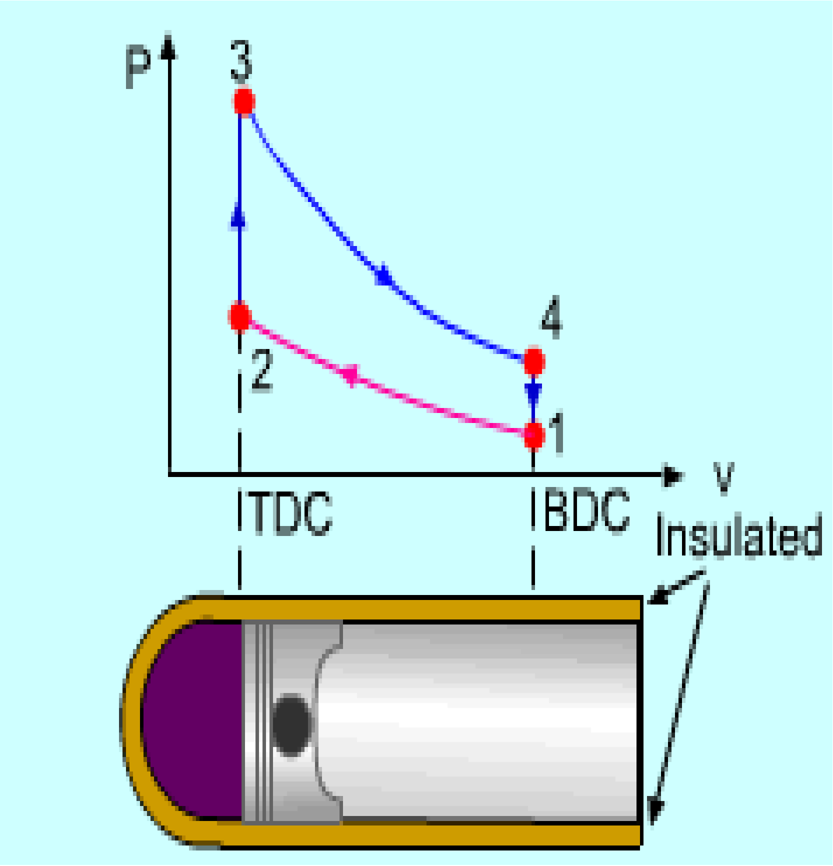
$$Q_H/Q_L = f(T_H,T_L)$$

Where Q_L= heat transferred to the low-temperature reservoir which has a temperature of T_L

Q_H = heat transferred from the high-temperature reservoir which has a temperature of T_H

g, f = any function

IDEAL OTTO CYCLE - IDEAL CYCLE FOR SPARK-IGNITION ENGINES



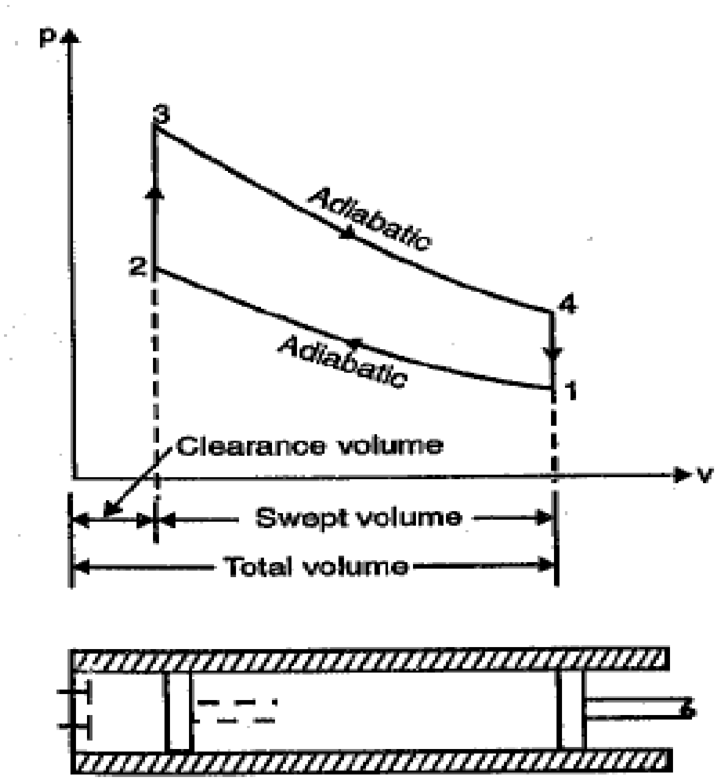
- Otto cycle is the ideal cycle for spark-ignition engines, in honor of Nikolaus Otto, who invented it in 1867.

- In ideal Otto cycles, air-standard assumption is used.

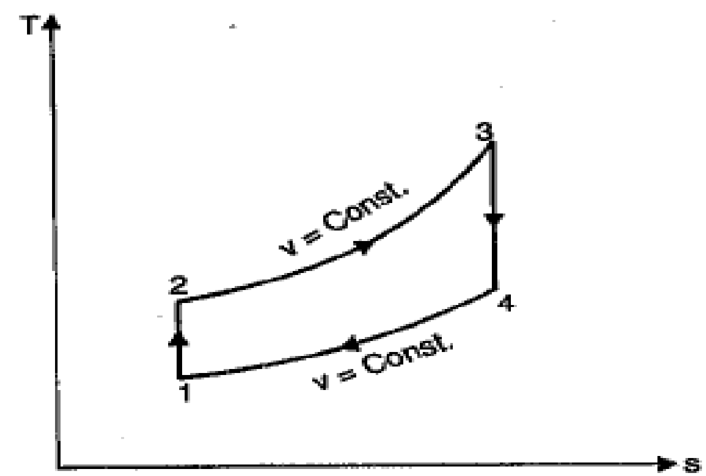
- The ideal Otto cycle consists of four internal reversible processes:

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

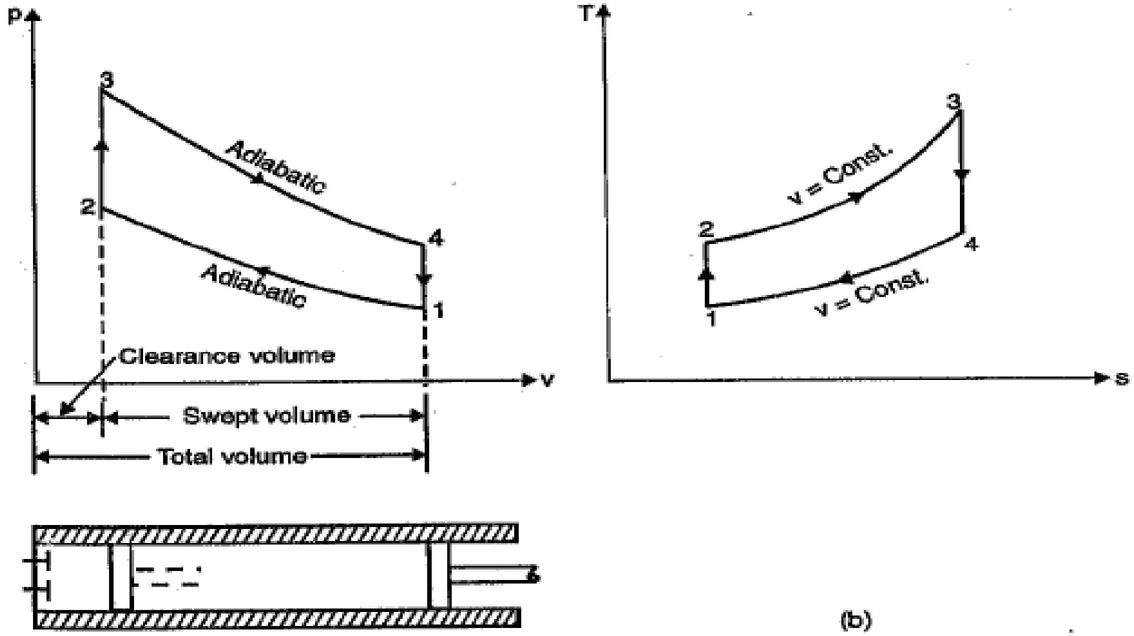
Otto cycle is the ideal cycle for spark-ignition



(a)



(b)



(a) (b)

Consider **1 kg of air** (working substance) :

Heat supplied at constant volume $= c_v(T_3 - T_2)$.

Heat rejected at constant volume $= c_v(T_4 - T_1)$.

But, work done = Heat supplied – Heat rejected

$$= c_v(T_3 - T_2) - c_v(T_4 - T_1)$$

$$\therefore \quad \text{Efficiency} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{c_v(T_3 - T_2) - c_v(T_4 - T_1)}{c_v(T_3 - T_2)}$$

$$= 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

Let compression ratio, $r_c (= r) = \frac{v_1}{v_2}$

and expansion ratio, $r_e (= r) = \frac{v_4}{v_3}$

(These *two ratios are same* in this cycle)

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

Then, $$T_2 = T_1 \,.\, (r)^{\gamma - 1}$$

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

or $$T_3 = T_4 \,.\, (r)^{\gamma - 1}$$

Inserting the values of T_2 and T_3 in equation (*i*), we get

$$\eta_{otto} = 1 - \frac{T_4 - T_1}{T_4 \,.\, (r)^{\gamma - 1} - T_1 \,.\, (r)^{\gamma - 1}} = 1 - \frac{T_4 - T_1}{r^{\gamma - 1}(T_4 - T_1)}$$

$$= 1 - \frac{1}{(r)^{\gamma - 1}}$$

This expression is known as the ***air standard efficiency of the Otto cycle.***

innovate achieve lead

Example:1

An engine working on Otto cycle has the following conditions : Pressure at the beginning of compression is 1 bar and pressure at the end of compression is 11 bar. Calculate the compression ratio and air-standard efficiency of the engine. Assume $\gamma = 1.4$.

Solution

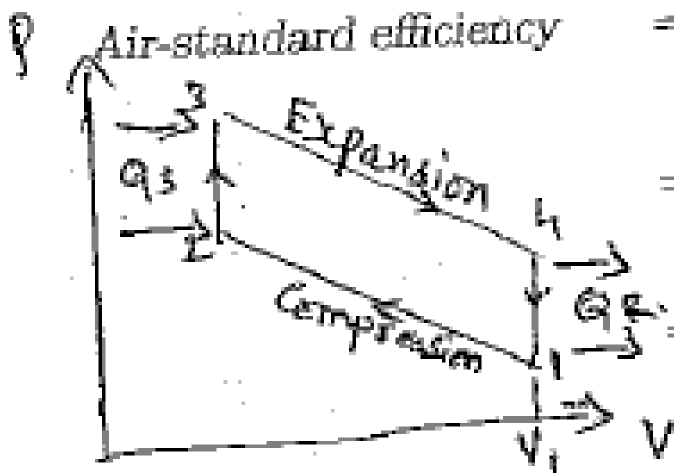
$$r = \frac{V_1}{V_2} = \left(\frac{p_2}{p_1}\right)^{\left(\frac{1}{\gamma}\right)} = 11^{\frac{1}{1.4}}$$

$$= 5.54 \quad \text{Ans}$$

$$\text{Air-standard efficiency} = 1 - \frac{1}{r^{\gamma-1}}$$

$$= 1 - \frac{1}{(5.54)^{0.4}} = 0.496$$

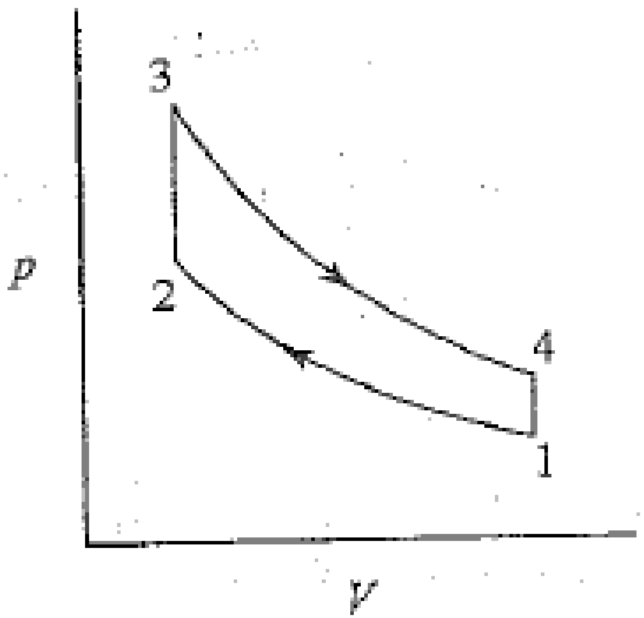
$$= 49.6\% \quad \text{Ans}$$



S. No	Process	Work done (W) KJ	P, V and T relations
1.	Constant Volume process V=C	Zero	$\frac{p_1}{T_1} = \frac{p_2}{T_2}$
2.	Constant pressure process P=C	$P(V_2 - V_1)$ Or $mR(T_2 - T_1)$	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$
3.	Constant temperature or Isothermal (T C)	$P_1V_1 \ln\left(\frac{V_2}{V_1}\right)$ Or $mRT_1 \ln\left(\frac{V_2}{V_1}\right)$	$P_1V_1 = p_2V_2$
4.	Reversible adiabatic or Isentropic process $pV^{\gamma} = C$	$\frac{p_1V_1 - p_2V_2}{\gamma - 1}$ or $\frac{mR(T_1 - T_2)}{\gamma - 1}$	$\frac{p_1}{p_2} = \left(\frac{V_2}{V_1}\right)^{\gamma}$ $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$ $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$

Example:2

In an Otto cycle air at 17 °C and 1 bar is compressed adiabatically until the pressure is 15 bar. Heat is added at constant volume until the pressure rises to 40 bar. Calculate the air-standard efficiency, the compression ratio and the mean effective pressure for the cycle. Assume $C_v = 0.717$ kJ/kg K and $R = 8.314$ kJ/kmol K.



Solution

Consider the process 1 − 2

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$$

$$\frac{V_1}{V_2} = r = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}}$$

BITS Pilani
Dubai Campus

innovate achieve lead

$$= \left(\frac{15}{1}\right)^{\frac{1}{1.4}} = 6.91$$

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma - 1} = 1 - \left(\frac{1}{6.91}\right)^{0.4}$$

$$= 0.539 = 53.9\% \quad \Longleftarrow \text{Ans}$$

$$T_2 = \frac{p_2 V_2}{p_1 V_1} T_1 = \frac{15}{1} \times \frac{1}{6.91} \times 290$$

$$= 629.5 \text{ K}$$

Consider the process 2 – 3

$$T_3 = \frac{p_3 T_2}{p_2} = \frac{40}{15} \times 629.5 = 1678.7$$

Consider the process 2 − 3

$$T_3 = \frac{p_3 T_2}{p_2} = \frac{40}{15} \times 629.5 = 1678.7$$

$$\text{Heat supplied} = C_v(T_3 - T_2)$$
$$= 0.717 \times (1678.7 - 629.5)$$
$$= 752.3 \text{ kJ/kg}$$

$$\text{Work done} = \eta \times q_s$$
$$= 0.539 \times 752.3 = 405.5 \text{ kJ/kg}$$

$$\eta_{bth} = \frac{bp}{\dot{m}_f \times CV}$$

$$p_m = \frac{\text{Work done}}{\text{Swept volume}}$$

$$v_1 = \frac{V_1}{m} = M\frac{RT_1}{p_1}$$

$$\frac{\frac{kJ}{kg\text{-mol-K}} \times K}{\frac{kg}{kmol} \times N/m^2} = m^3/kg$$

$$= \frac{8314 \times 290}{29 \times 1 \times 10^5} = 0.8314 \text{ m}^3/\text{kg}$$

BITS Pilani
Dubai Campus

innovate achieve lead

$$v_1 - v_2 = \frac{5.91}{6.91} \times 0.8314 = 0.711 \text{ m}^3/\text{kg}$$

$$p_m = \frac{405.5}{0.711} \times 10^3 = 5.70 \times 10^5 \text{ N/m}^2$$

$$= 5.70 \text{ bar}$$

Ans

Example:3

3.3 A gas engine working on the Otto cycle has a cylinder of diameter 200 mm and stroke 250 mm. The clearance volume is 1570 cc. Find the air-standard efficiency. Assume $C_p = 1.004$ kJ/kg K and $C_v = 0.717$ kJ/kg K for air.

Solution

$$\text{Stroke volume, } V_s = \frac{\pi}{4} d^2 L = \frac{\pi}{4} \times 20^2 \times 25$$

$$= 7853.98 \text{ cc}$$

$$\text{Compression ratio, } r = 1 + \frac{V_s}{V_c} = 1 + \frac{7853.98}{1570}$$

$$= 6.00$$

$$\gamma = \frac{C_p}{C_v} = \frac{1.004}{0.717} = 1.4$$

$$\text{Air-standard efficiency} = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{6^{(0.4)}}$$

$$= 0.512 = 51.2\%$$

$\Leftarrow$ Ans

Example:4

Example 21.9. *The minimum pressure and temperature in an Otto cycle are 100 kPa and 27°C. The amount of heat added to the air per cycle is 1500 kJ/kg.*

(i) Determine the pressures and temperatures at all points of the air standard Otto cycle.

(ii) Also calculate the specific work and thermal efficiency of the cycle for a compression ratio of 8 : 1.

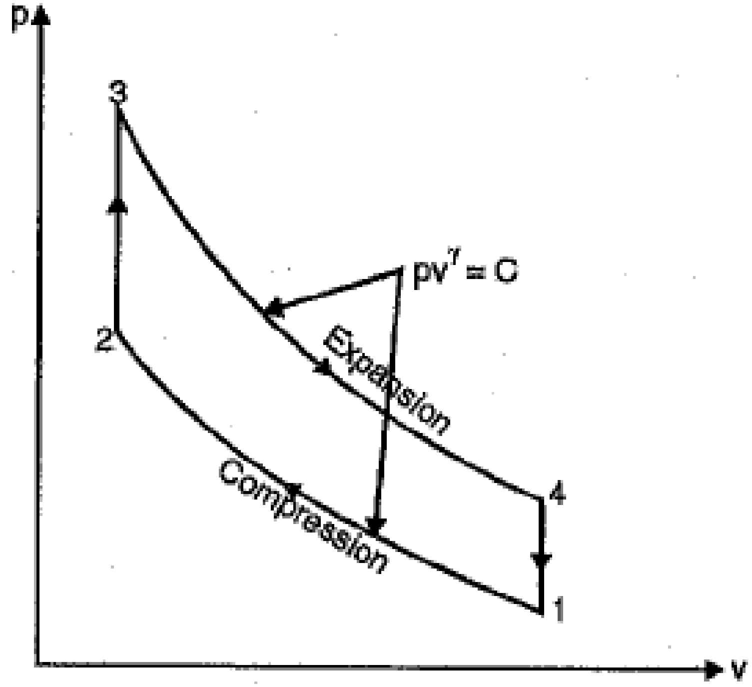
Take for air : c_v = 0.72 kJ/kg K, and γ = 1.4. **(GATE, 1998)**

Solution. Refer Fig. 21.7. *Given* : p_1 = 100 kPa = 10^5 N/m² or 1 bar ;

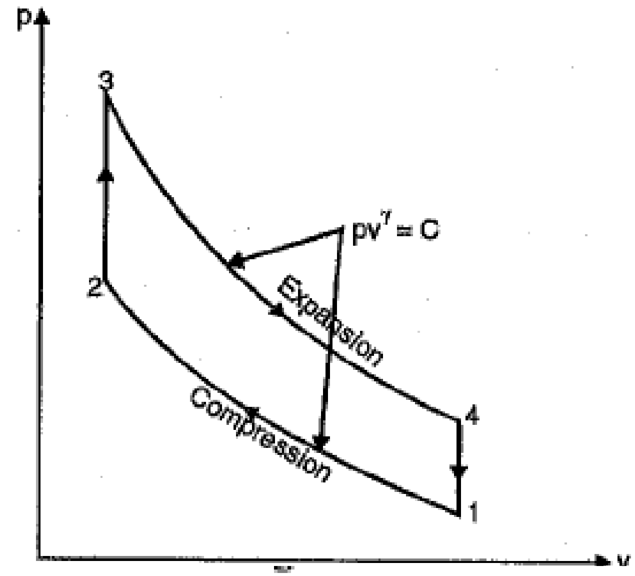
T_1 = 27 + 273 = 300 K ; Heat added = 1500 kJ/kg ;

r = 8 : 1 ; c_v = 0.72 kJ/kg ; γ = 1.4.

Consider 1 kg of air.



Consider 1 kg of air.



(i) Pressures and temperatures at all points :

Adiabatic compression process 1-2 :

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1} = (r)^{\gamma - 1} = (8)^{1.4 - 1} = 2.297$$

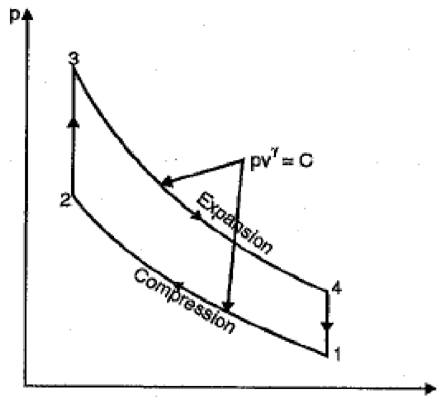
∴ $$\mathbf{T_2 = 300 \times 2.297 = 689.1\ K.} \quad \textbf{(Ans.)}$$

Also $$p_1 v_1^{\gamma} = p_2 v_2^{\gamma}$$

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = (8)^{1.4} = 18.379$$

∴ $$\mathbf{p_2 = 1 \times 18.379 = 18.379\ bar.} \quad \textbf{(Ans.)}$$

Consider 1 kg of air.



Constant volume process 2-3 :

Heat added during the process,

$$c_v (T_3 - T_2) = 1500$$

or $$0.72 (T_3 - 689.1) = 1500$$

or $$T_3 = \frac{1500}{0.72} + 689.1 = 2772.4 \text{ K. (Ans.)}$$

Also, $$\frac{p_2}{T_2} = \frac{p_3}{T_3} \Rightarrow p_3 = \frac{p_2 T_3}{T_2} = \frac{18.379 \times 2772.4}{689.1} = 73.94 \text{ bar. (Ans.)}$$

Adiabatic Expansion process 3-4 :

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma - 1} = (r)^{\gamma - 1} = (8)^{1.4 - 1} = 2.297$$

$\therefore$ $$T_4 = \frac{T_3}{2.297} = \frac{2772.4}{2.297} = 1206.9 \text{ K. (Ans.)}$$

Also, $$p_3 v_3^{\gamma} = p_4 v_4^{\gamma} \Rightarrow p_4 = p_3 \times \left(\frac{v_3}{v_4}\right)^{\gamma} = 73.94 \times \left(\frac{1}{8}\right)^{1.4} = 4.023 \text{ bar. (Ans.)}$$

(ii) **Specific work and thermal efficiency :**

Specific work = Heat added – heat rejected

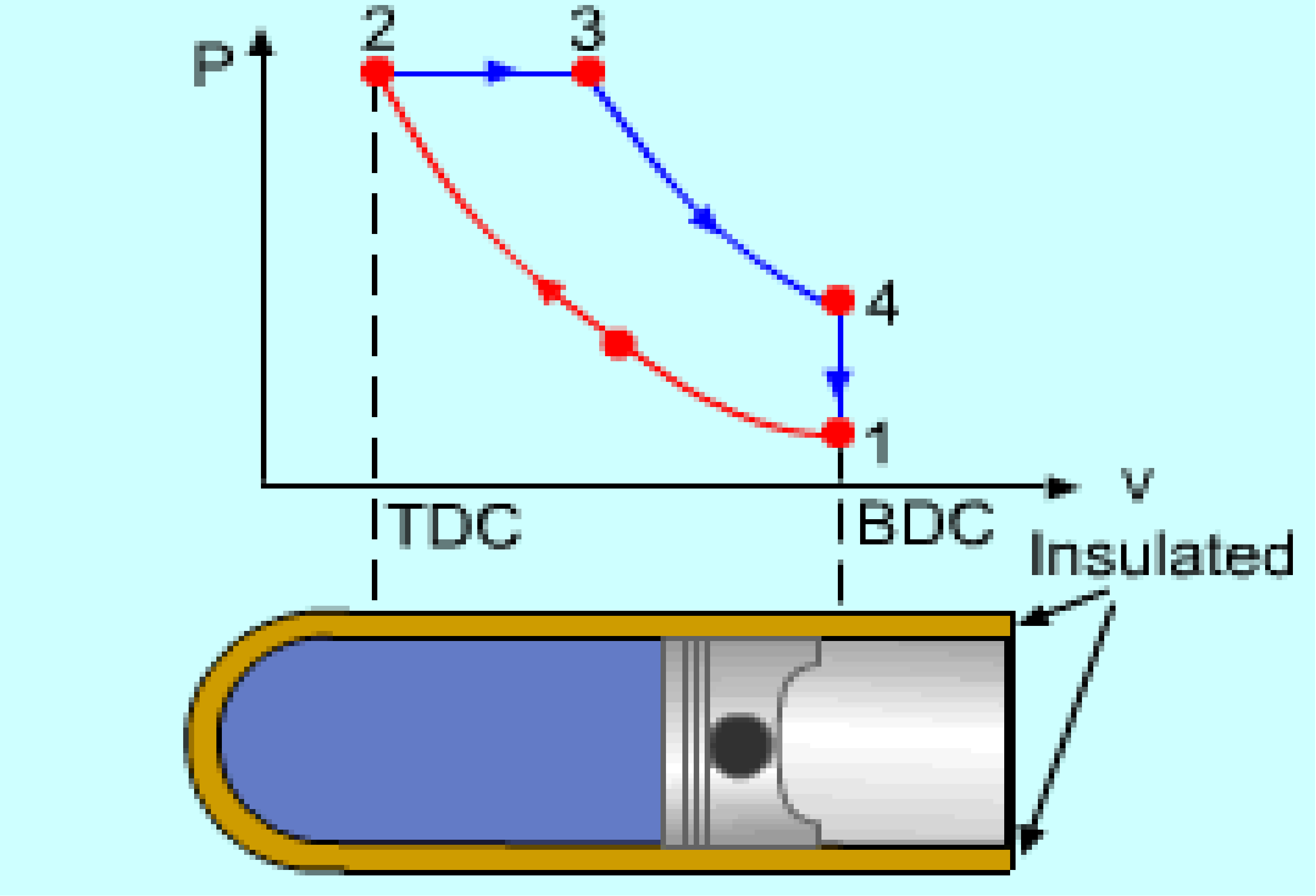
$$= c_v (T_3 - T_2) - c_v(T_4 - T_1) = c_v [(T_3 - T_2) - (T_4 - T_1)]$$

$$= 0.72\,[(2772.4 - 689.1) - (1206.9 - 300)] = \mathbf{847\ kJ/kg.} \quad \text{(Ans.)}$$

Thermal efficiency, $\eta_{th} = 1 - \dfrac{1}{(r)^{\gamma - 1}}$

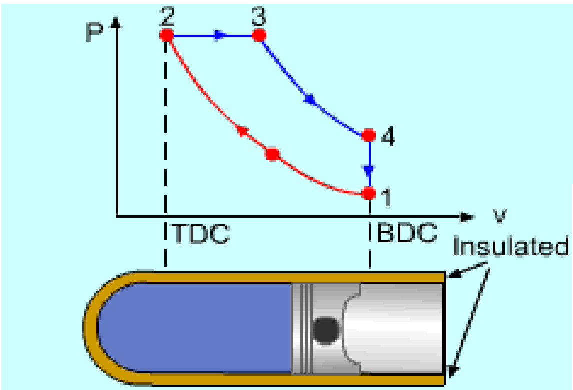
$$= 1 - \frac{1}{(8)^{1.4 - 1}} = 0.5647 \quad \text{or} \quad \mathbf{56.47\%.} \quad \text{(Ans.)}$$

Diesel Cycle - Ideal Cycle for Compression-ignition Engines



Example:1

A Diesel engine has a compression ratio of 20 and cut-off takes place at 5% of the stroke. Find the air-standard efficiency. Assume $\gamma = 1.4$.



Solution

$$V_s = 20V_2 - V_2 = 19V_2$$

$$V_3 = 0.05V_s + V_2 = 0.05 \times 19V_2 + V_2 = 1.95V_2$$

$$r_c = \frac{V_3}{V_2} = \frac{1.95V_2}{V_2} = 1.95$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}$$

$$= 1 - \frac{1}{20^{0.4}} \times \left[\frac{1.95^{1.4} - 1}{1.4 \times (1.95 - 1)}\right] = 0.649$$

$$= 64.9\%$$

Ans ⟸

Example:2

3.12 Determine the ideal efficiency of the diesel engine having a cylinder with bore 250 mm, stroke 375 mm and a clearance volume of 1500 cc, with fuel cut-off occurring at 5% of the stroke. Assume $\gamma = 1.4$ for air.

Solution

$$V_s = \frac{\pi}{4} d^2 L = \frac{\pi}{4} \times 25^2 \times 37.5$$

$$= 18407.8 \text{ cc}$$

$$r = 1 + \frac{V_s}{V_c} = 1 + \frac{18407.8}{1500} = 13.27$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}$$

$$r_c = \frac{V_3}{V_2}$$

Example:3

Determine the ideal efficiency of the diesel engine having a cylinder with bore 250 mm, stroke 375 mm and a clearance volume of 1500 cc, with fuel cut-off occurring at 5% of the stroke. Assume $\gamma = 1.4$ for air.

Solution

$$V_s = \frac{\pi}{4} d^2 L = \frac{\pi}{4} \times 25^2 \times 37.5$$

$$= 18407.8 \text{ cc}$$

$$r = 1 + \frac{V_s}{V_c} = 1 + \frac{18407.8}{1500} = 13.27$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}$$

$$r_c = \frac{V_3}{V_2}$$

Example:4

$$\text{Cut-off volume} = V_3 - V_2 = 0.05 V_s$$

$$= 0.05 \times 12.27 V_c$$

$$V_2 = V_c$$

$$V_3 = 1.6135 V_c$$

$$r_c = \frac{V_3}{V_2} = 1.6135$$

$$\eta = 1 - \frac{1}{13.27^{0.4}} \times \frac{1.6135^{1.4} - 1}{1.4 \times (1.6135 - 1)}$$

$$= 0.6052 = 60.52\%$$

Ans

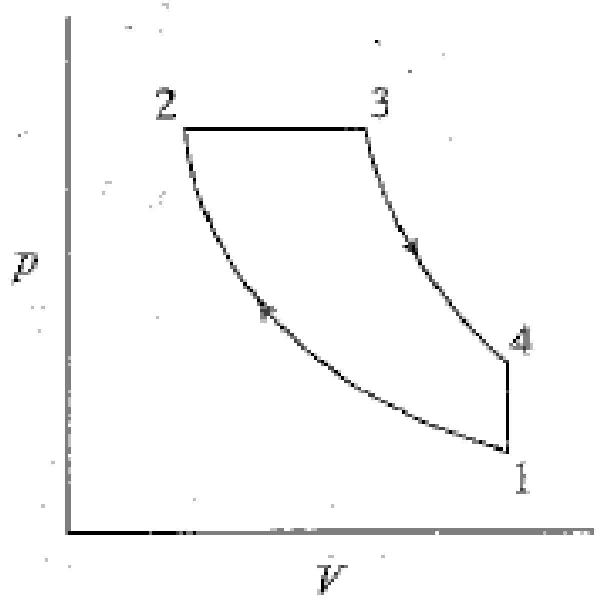
BITS Pilani
Dubai Campus

innovate achieve lead

Example:5

In an engine working on Diesel cycle inlet pressure and temperature are 1 bar and 17 °C respectively. Pressure at the end of adiabatic compression is 35 bar. The ratio of expansion i.e. after constant pressure heat addition is 5. Calculate the heat addition, heat rejection and the efficiency of the cycle. Assume $\gamma = 1.4$, $C_p = 1.004$ kJ/kg K and $C_v = 0.717$ kJ/kg K.

Solution



Consider the process 1 − 2

$$\frac{V_1}{V_2} = r = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} = \left(\frac{35}{1}\right)^{\frac{1}{1.4}} = 12.674$$

$$\text{Cut-off ratio} = \frac{V_3}{V_2} = \frac{V_3}{V_1} \times \frac{V_1}{V_2}$$

$$= \frac{\text{Compression ratio}}{\text{Expansion ratio}} = \frac{12.674}{5} = 2.535$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{35}{1}\right)^{0.286} = 2.76$$

$$T_2 = 2.76 \times 290 = 801.7 \text{ K}$$

Consider the process 2 − 3

$$T_3 = T_2\frac{V_3}{V_2} = 801.7 \times \frac{V_3}{V_2}$$

$$= 801.7 \times 2.535 = 2032.3 \text{ K}$$

BITS Pilani
Dubai Campus

innovate achieve lead

Consider the process 3 – 4

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{\gamma-1} = 2032.3 \times \left(\frac{1}{5}\right)^{0.4}$$

$$= 1067.6 \text{ K}$$

$$\text{Heat added} = C_p(T_3 - T_2) = 1.004 \times (2032.3 - 801.7)$$

$$= \mathbf{1235.5\ kJ/kg} \quad \underleftarrow{\text{Ans}}$$

$$\text{Heat rejected} = C_v(T_4 - T_1) = 0.717 \times (1067.6 - 290)$$

$$= \mathbf{557.5\ kJ/kg} \quad \underleftarrow{\text{Ans}}$$

$$\text{Efficiency} = \frac{\text{Heat supplied - Heat rejected}}{\text{Heat supplied}}$$

$$= \frac{1235.5 - 557.5}{1235.5} = 0.549 = 54.9\% \quad \underleftarrow{\text{Ans}}$$

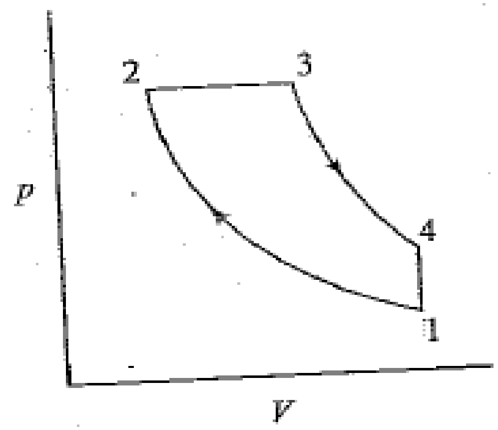
BITS Pilani
Dubai Campus

innovate achieve lead

Example:6

3.14 A Diesel engine is working with a compression ratio of 15 and expansion ratio of 10. Calculate the air-standard efficiency of the cycle. Assume $\gamma = 1.4$.

Solution



$$r = \frac{V_1}{V_2} = 15$$

$$r_e = \frac{V_4}{V_3} = 10$$

$$\eta = 1 - \frac{1}{\gamma}\frac{1}{r^{\gamma-1}}\left[\frac{\left(\frac{r}{r_e}\right)^{\gamma} - 1}{\left(\frac{r}{r_e}\right) - 1}\right]$$

$$= \quad 1 - \frac{1}{1.4} \times \frac{1}{15^{0.4}} \times \left[\frac{\left(\frac{15}{10}\right)^{1.4} - 1}{\left(\frac{15}{10}\right) - 1} \right] \quad = \quad 0.63$$

$$= \quad 63\%$$

Ans

Example:7

Example 21.22. *The volume ratios of compression and expansion for a diesel engine as measured from an indicator diagram are 15.3 and 7.5 respectively. The pressure and temperature at the beginning of the compression are 1 bar and 27°C.*

Assuming an ideal engine, determine the mean effective pressure, the ratio of maximum pressure to mean effective pressure and cycle efficiency.

Also find the fuel consumption per kWh if the indicated thermal efficiency is 0.5 of ideal efficiency, mechanical efficiency is 0.8 and the calorific value of oil 42000 kJ/kg.

Assume for air : $c_p = 1.005$ *kJ/kg K ;* $c_v = 0.718$ *kJ/kg K,* $\gamma = 1.4$. **(U.P.S.C., 1996)**

Solution. Refer Fig. 21.18. *Given :* $\frac{V_1}{V_2} = 15.3$; $\frac{V_4}{V_3} = 7.5$

$p_1 = 1$ bar ; $T_1 = 27 + 273 = 300$ K ; $\eta_{th(I)} = 0.5 \times \eta_{air\text{-}standard}$; $\eta_{mech.} = 0.8$; $C = 42000$ kJ/kg.

The cycle is shwon in Fig. 21.18, the subscripts denote the respective points in the cycle.

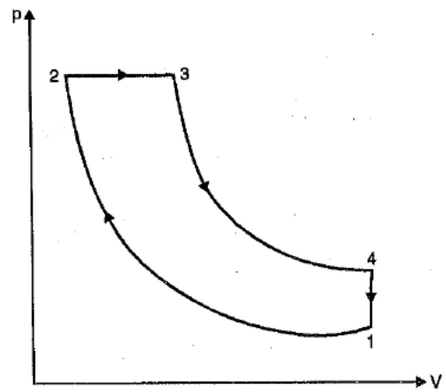


Fig. 21.18. Diesel cycle.

Mean effective pressure, p_m :

$$p_m = \frac{\text{Work done by the cycle}}{\text{Swept volume}}$$

Work done $= \text{Heat added} - \text{heat rejected}$

Heat added $= mc_p\,(T_3 - T_2)$, and

Heat rejected $= mc_v\,(T_4 - T_1)$

Now assume air as a perfect gas and mass of oil in the air-fuel mixture is negligible and is not taken into account.

Process 1-2 is an adiabatic compression process, thus

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \quad \text{or} \quad T_2 = T_1 \times \left(\frac{V_1}{V_2}\right)^{1.4-1} \quad (\text{since } \gamma = 1.4)$$

or $$T_2 = 300 \times (15.3)^{0.4} = 893.3 \text{ K}$$

Also, $$p_1V_1^{\gamma} = p_2V_2^{\gamma} \Rightarrow p_2 = p_1 \times \left(\frac{V_1}{V_2}\right)^{\gamma} = 1 \times (15.3)^{1.4} = 45.56 \text{ bar}$$

BITS Pilani
Dubai Campus

innovate achieve lead

Process 2-3 is a *constant pressure process*, hence

$$\frac{V_2}{T_2} = \frac{V_3}{T_3} \Rightarrow T_3 = \frac{V_3 T_2}{V_2} = 2.04 \times 893.3 = 1822.3 \text{ K}$$

Assume that the volume at point 2 (V_2) is 1 m³. Thus the mass of air involved in the process

$$m = \frac{p_2 V_2}{RT_2} = \frac{45.56 \times 10^5 \times 1}{287 \times 893.3} = 17.77 \text{ kg}$$

$$\left[\because \quad \frac{V_4}{V_3} = \frac{V_1}{V_3} = \frac{V_1}{V_2} \times \frac{V_2}{V_3} \quad \text{or} \quad \frac{V_3}{V_2} = \frac{V_1}{V_2} \times \frac{V_3}{V_4} = \frac{15.3}{7.5} = 2.04 \right]$$

Process 3-4 is an *adiabatic expansion process*, thus

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma - 1} = \left(\frac{1}{7.5}\right)^{1.4-1} = 0.4466$$

or $T_4 = 1822.3 \times 0.4466 = 813.8$ K

$\therefore$ Work done $= mc_p (T_3 - T_2) - mc_v (T_4 - T_1)$

$= 17.77 [1.005 (1822.3 - 893.3) - 0.718 (813.8 - 300)] = 10035$ kJ

$$\therefore \quad p_m = \frac{\text{Work done}}{\text{Swept volume}} = \frac{10035}{(V_1 - V_2)} = \frac{10035}{(15.3 V_2 - V_2)} = \frac{10035}{14.3}$$

$= 701.7$ kN/m² $=$ **7.017 bar. (Ans.)**

($\because$ $V_2 = 1$ m³ assumed)

Ratio of maximum pressure to mean effective pressure

$$= \frac{p_2}{p_m} = \frac{45.56}{7.017} = \mathbf{6.49.} \quad \textbf{(Ans.)}$$

Cycle efficiency, η_{cycle} :

$$\eta_{cycle} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{10035}{mc_p\,(T_3 - T_2)} = \frac{10035}{17.77 \times 1.005\,(1822.3 - 897.3)} = \mathbf{0.6048} \quad \textbf{or} \quad \mathbf{60.48\%.} \quad \textbf{(Ans.)}$$

Fuel consumption per kWh ; m_f :

$$\eta_{th(I)} = 0.5\ \eta_{cycle} = 0.5 \times 0.6048 = 0.3024 \quad \text{or} \quad 30.24\%$$

$$\eta_{th(B)} = 0.3024 \times 0.8 = 0.242$$

Also,

$$\eta_{th(B)} = \frac{\text{B.P.}}{m_f \times C} = \frac{1}{\frac{m_f}{3600} \times 42000} = \frac{3600}{m_f \times 42000}$$

$$0.242 = \frac{3600}{m_f \times 42000}$$

$$\mathbf{m_f} = \frac{3600}{0.242 \times 42000} = \mathbf{0.354\ kg/kWh.} \quad \textbf{(Ans.)}$$

21.6. DUAL COMBUSTION CYCLE

This cycle (also called the *limited pressure cycle or mixed cycle*) is a combination of Otto and Diesel cycles, in a way, that heat is added partly at constant volume and partly at constant pressure ; *the advantage of which is that more time is available to fuel (which is injected into the engine cylinder before the end of compression stroke) for combustion. Because of lagging characteristics of fuel this cycle is invariably used for diesel and hot spot ignition engines.*

The dual combustion cycle (Fig. 21.19) consists of the following **operations** :

(*i*) 1-2—*Adiabatic compression*

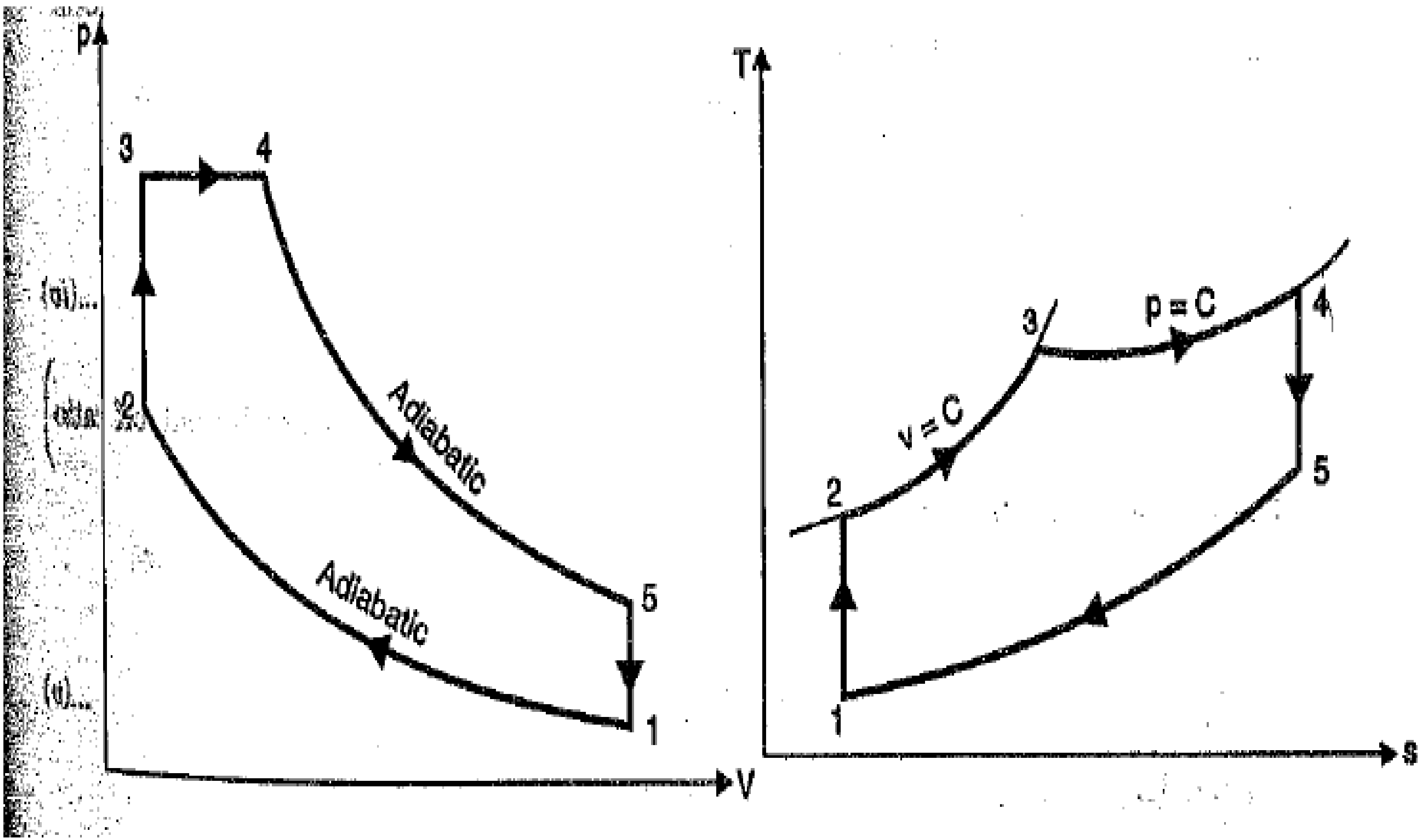
(*ii*) 2-3—*Addition of heat at constant volume*

(*iii*) 3-4—*Addition of heat at constant pressure*

(*iv*) 4-5—*Adiabatic expansion*

(*v*) 5-1—*Rejection of heat at constant volume.*

DUAL CYCLES



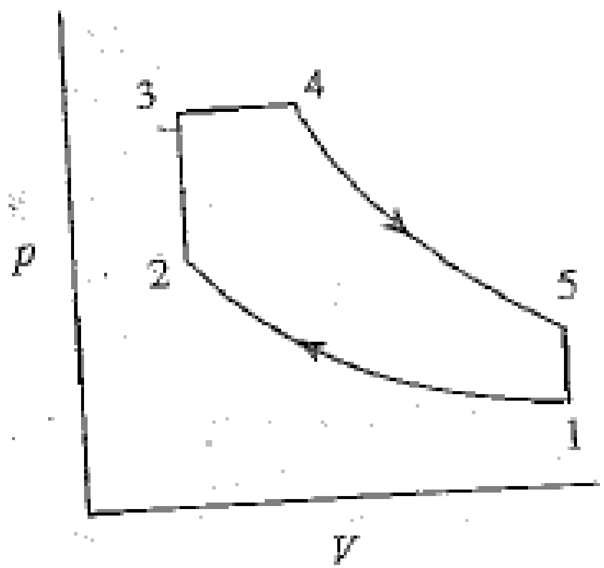
BITS Pilani
Dubai Campus

innovate achieve lead

Example:1

For an engine working on the ideal Dual cycle, the compression ratio is 10 and the maximum pressure is limited to 70 bar. If the heat supplied is 1680 kJ/kg, find the pressures and temperatures at the various salient points of the cycle and the cycle efficiency. The pressure and temperature of air at the commencement of compression are 1 bar and 100 °C respectively. Assume $C_p = 1.004$ kJ/kg K and $C_v = 0.717$ kJ/kg K for air.

Solution



BITS Pilani
Dubai Campus

innovate achieve lead

Heat added during constant volume combustion

$$= C_v (T_3 - T_2)$$

$$= 0.717 \times (2611.1 - 936.9) = 1200.4 \text{ kJ/kg}$$

Total heat added $= 1680$ kJ/kg

Hence, heat added during constant pressure combustion

$$= 1680 - 1200.4 = 479.6 \text{ kJ/kg}$$

$$= C_p (T_4 - T_3)$$

$$T_4 - T_3 = \frac{479.6}{1.004} = 477.7 \text{ K}$$

$$T_4 = 477.7 + 2611.1 = 3088.8 \text{ K}$$

$$= \mathbf{2815.8^\circ\ C} \quad \xLeftarrow{\text{Ans}}$$

$$\text{Cut-off ratio, } r_c = \frac{V_4}{V_3} = \frac{T_4}{T_3} = \frac{3088.8}{2611.1} = 1.183$$

Consider the process 4 – 5

$$\frac{T_4}{T_5} = \left(\frac{r}{r_c}\right)^{(\gamma-1)} = 8.453^{0.4} = 2.35$$

$$T_5 = \frac{T_4}{2.35} = \frac{3088.8}{2.35} = 1314.4 \text{ K}$$

$$= 1041.4^\circ \text{ C} \quad \underleftarrow{\text{Ans}}$$

$$\frac{p_4}{p_5} = \left(\frac{r}{r_c}\right)^{\gamma} = 19.85$$

$$p_5 = \frac{p_4}{19.85} = \frac{70 \times 10^5}{19.85}$$

$$= 3.53 \times 10^5 \text{ N/m}^2 = \mathbf{3.53 \text{ bar}} \quad \underleftarrow{\text{Ans}}$$

$$\text{Heat rejected} = C_v(T_5 - T_1)$$

$$= 0.717 \times (1314.4 - 373) = 674.98 \text{ kJ/kg}$$

$$\eta = \frac{1680 - 674.98}{1680} = \mathbf{59.82\%} \quad \underleftarrow{\text{Ans}}$$

BITS Pilani
Dubai Campus

innovate achieve lead

$$\frac{V_s}{V_c} = r - 1 = 9$$

$$\gamma = \frac{C_p}{C_v} = \frac{1.004}{0.717} = 1.4$$

Consider the process 1 – 2

$$\frac{p_2}{p_1} = r^{\gamma} = 10^{1.4} = 25.12$$

$$p_2 = 25.12 \times 10^5 \text{ N/m}^2 = 25.12 \text{ bar}$$ Ans

$$\frac{T_2}{T_1} = r^{(\gamma-1)} = 10^{0.4} = 2.512$$

$$T_2 = 2.512 \times 373 = 936.9 \text{ K} = 663.9°\text{C}$$ Ans

Consider the process 2 – 3 and 3 – 4

$$\frac{T_3}{T_2} = \frac{p_3}{p_2} = \frac{70}{25.12} = 2.787$$

$$T_3 = 2.787 \times 936.9 = 2611.1 \text{ K}$$

$$= 2338° \text{ C}$$ Ans