IARE

INSTITUTE OF AERONAUTICAL ENGINEERING

Course Title: Engineering Thermodynamics

Topic: MODULE V

Presenter's Name – Dr. G. Hima Bindu

Presenter's ID – IARE11099

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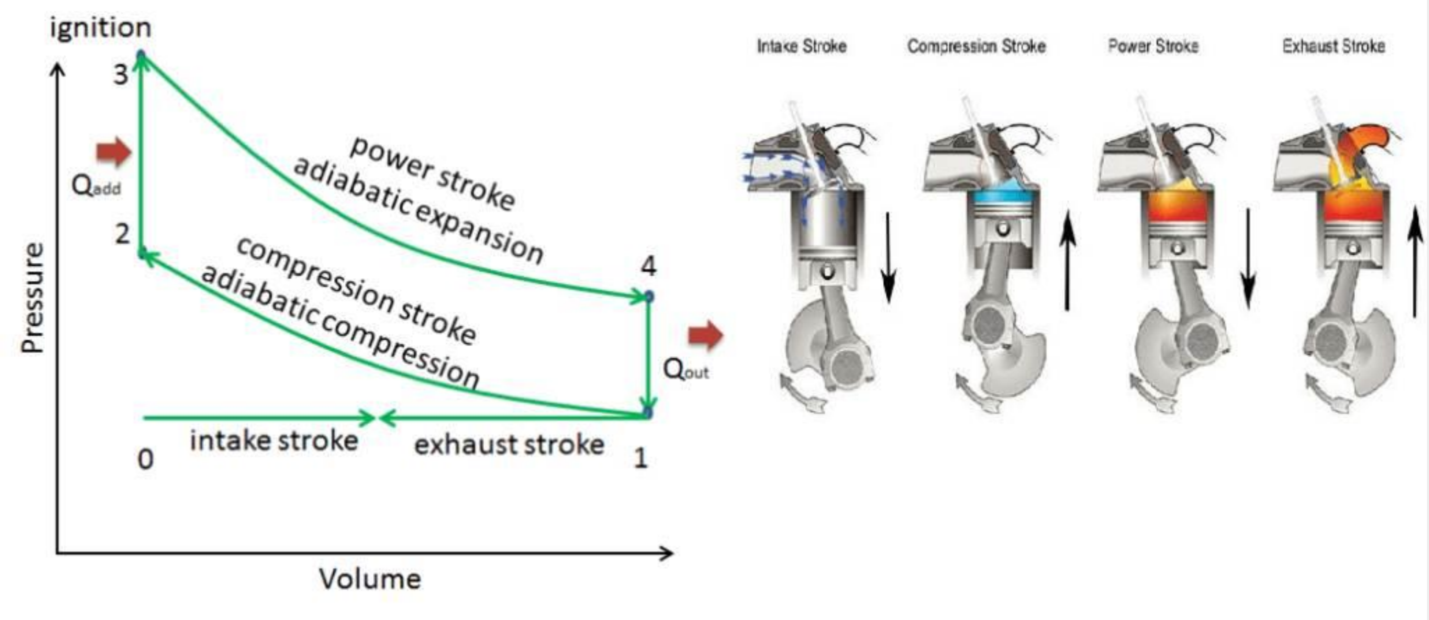
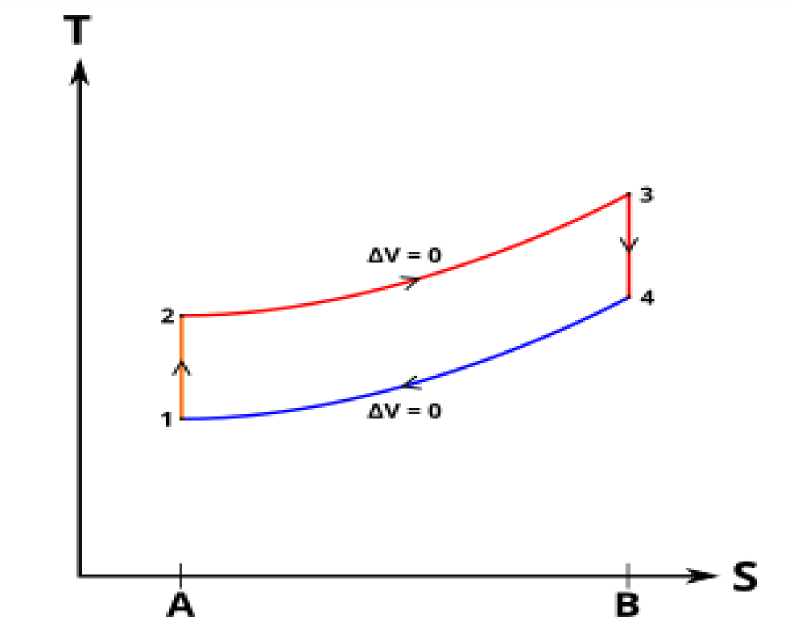
Otto cycle

The Otto cycle, also referred to as the spark-ignition cycle, is the fundamental thermodynamic cycle used in petrol engines. It operates on the principle of constant volume combustion and consists of four processes: intake, compression, combustion, and exhaust.





1-2 (Adiabatic process): In this process compression takes place, as the piston moves from BDC to TDC increasing its temperature

2-3 (Isochoric process): In this process, ignition is taking place, combustion happens when the piston is at TDC and pressure increases at a constant volume.

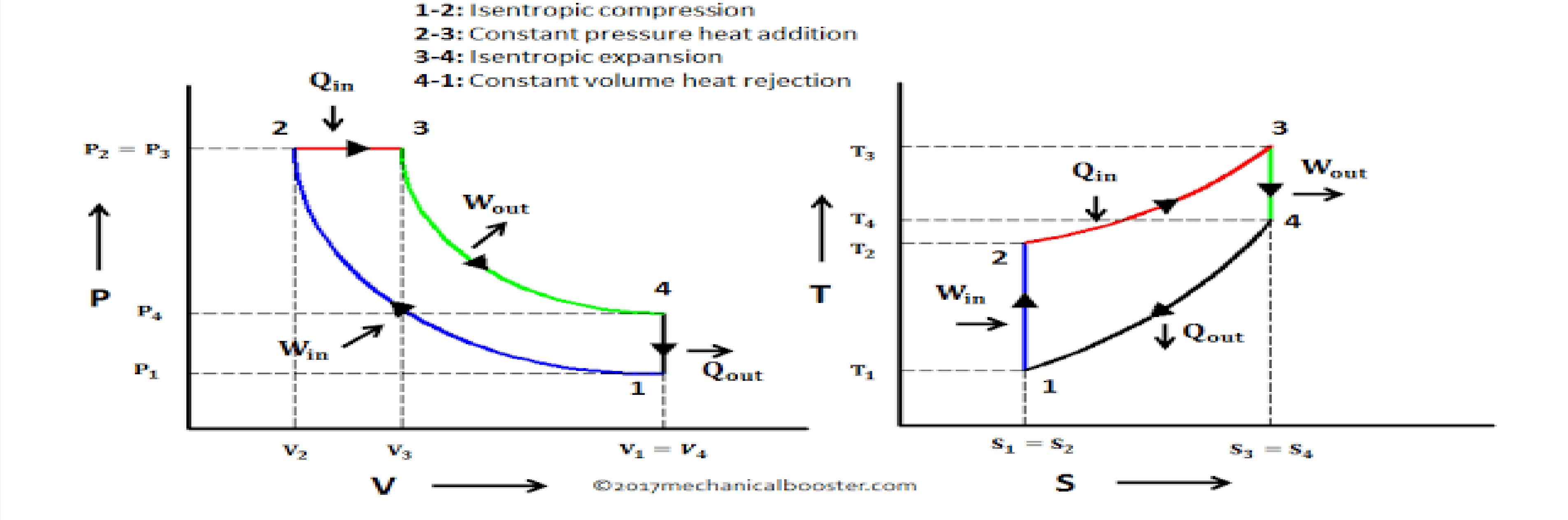
3-4 (Adiabatic process): In this process expansion is taking place, the heat produced due to the combustion pushes the piston down which rotates the crankshaft.

4-1 (Isochoric process): In this process, heat rejection is taking place at constant volume.

- The compression ratio of the otto cycle is 8 to 12.
- The efficiency of otto cycle is $\eta = 1 - \left(\frac{1}{CR}\right)^{\gamma-1}$

Diesel cycle

The Diesel cycle is a thermodynamic process that is commonly used in diesel engines for internal combustion. It operates on the principle of constant pressure combustion and consists of four distinct processes: intake, compression, combustion, and exhaust.



P-V and T-S Diagram of Diesel Cycle

1-2 In this process suction takes place

2-3 (Adiabatic process) In this process compression takes place. Both the inlet and exhaust valves are closed and the compression takes place which is much higher than that of an otto cycle. This increases the pressure and temperature.

3-4 (Isobaric process) In this process, fuel is added, and combustion occurs due to high temperature, while maintaining a constant pressure because the volume is also increasing.

4-5 (Adiabatic process) In this process expansion takes place, due to combustion the piston moves from TDC to BDC and power is generated.

5-2 (Isochoric process) In this process, heat rejection is taking place at constant volume.

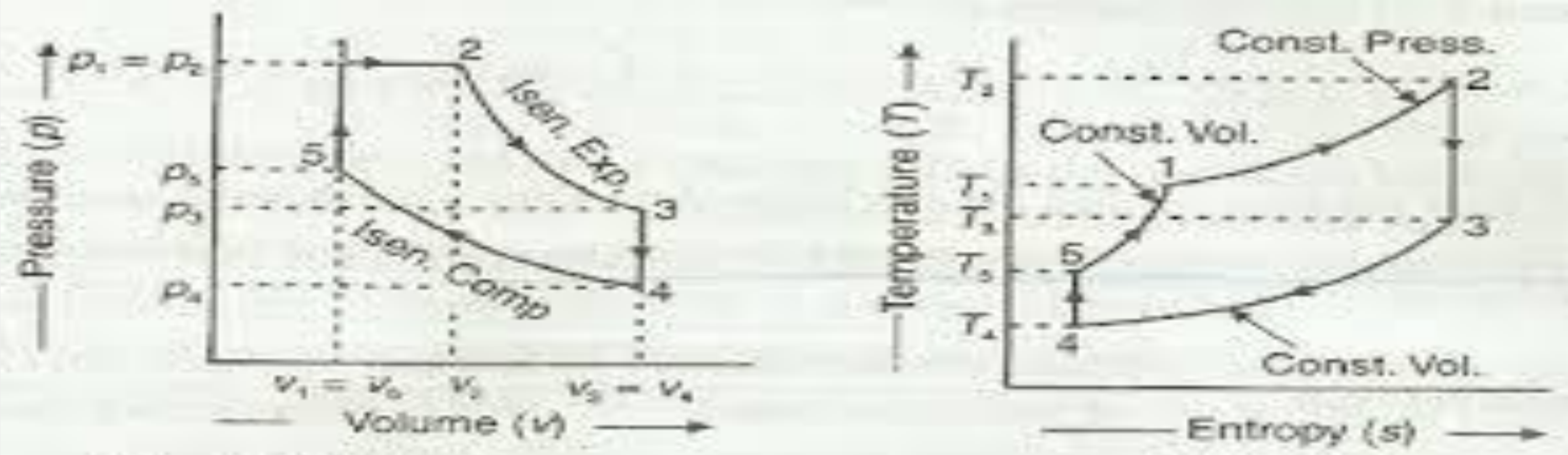
- Compression ratio is 14 to 22.

Efficiency of diesel cycle is

$$\eta = 1 - \frac{1}{\gamma(\frac{V_1}{V_2})^{\gamma-1}} \left[\frac{(\frac{V_3}{V_2})^{\gamma}-1}{\frac{V_3}{V_2}-1} \right]$$

Dual Cycle

The dual cycle is a combination of the Diesel cycle and Otto cycle, incorporating elements of both processes. Some advanced internal combustion engines employ it to achieve improved efficiency and performance, as seen in ship engines. The dual cycle consists of five processes: intake, compression, combustion, expansion, and exhaust.



(a) p-v diagram. (b) T-s diagram.

Fig. 5.13

1-2 (Adiabatic process) In this process compression takes place when the piston is going from BDC to TDC.

2-3 (Isochoric process) In this process fuel injection takes place when the piston is at TDC and suddenly the pressure increases at constant volume.

3-4 (Isobaric process) In this process, the engine adds fuel after reaching top dead center (TDC), while the piston descends, causing an increase in volume while maintaining constant pressure.

4-5 (Adiabatic process) In this process, the piston undergoes expansion, moving from top dead center (TDC) to bottom dead center (BDC), and generates power.

5-1 (Isochoric process) In this process heat rejection takes place at constant volume.

Difference between Otto cycle and Diesel cycle

Otto cycle	Diesel cycle
1. Otto cycle has low thermal efficiency	1. Diesel cycle has high thermal efficiency
2.It has low compression ratio	2. It has high compression ratio
3. It is also called constant volume cycle	3. It has constant pressure cycle
4. Explosion takes place at a constant volume	4. Explosion takes place at a constant pressure
5. Fuel used is petrol	5. Fuel used is diesel
6. The mixture of air and fuel is entered during the suction stroke	6. There is only air entering
7.Fuel and air mixture enters via carburetor	7.Fuel enters via fuel injector

PROBLEMS

1. A certain quantity of air at a pressure of 1 bar and temperature of 70^0C is compressed adiabatically until the pressure is 7 bar in Otto cycle engine. 465 KJ of heat per kg of air is now added at constant volume. Determine:

(i) Compression ratio of the engine

(ii) Temperature at the end of the compression

(iii) Temperature at the end of the heat addition

Assuming C_P and C_v for air is 1 KJ/kg K and 0.706 KJ/kg K

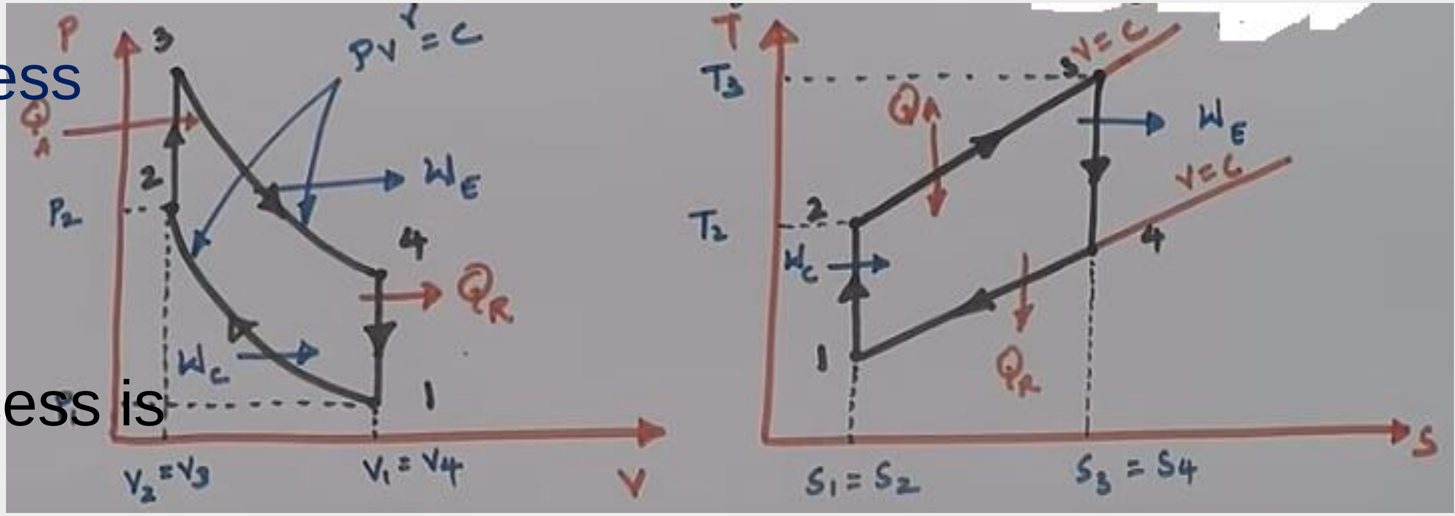
Given data

P_1= 1 bar = 10^5 N/m^2 ; P_2= 7 bar = 7 x 10^5 N/m^2

T_1= 70^0 C = 70+273 = 343 K ; Q_A= 465 KJ/kg ; m = 1 kg

Find (i) $r_c = ?$ $(ii)\ T_2 = ?$ $(iii)\ T_3 = ?$

Sol:



(i) For process 1 – 2 isentropic process

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Therefore $P_1 {V_1}^{\gamma} = P_2 {V_2}^{\gamma}$, since process is reversible isentropic process

$$\left(\frac{V_1}{V_2}\right)^{\gamma} = \frac{P_2}{P_1} = \left(\frac{7\ x\ 10^5}{10^5}\right)$$

$$r_c = 7^{\frac{1}{\gamma}}$$

$$r_c = \frac{cylinder\ volume}{clearence\ volume} = \frac{V_1}{V_2}$$

Adiabatic index γ = $\frac{\boldsymbol{C_P}}{\boldsymbol{C_v}} = \frac{1}{0.706} = 1.41$

$r_c = 7^{\frac{1}{1.41}}$ = 3.975

(ii) Temperature at the end of the compression

$\frac{T_2}{T_1} = (\frac{V_1}{V_2})^{\gamma-1}$

$\frac{T_2}{T_1} = (r_c)^{\gamma-1} = (3.975)^{1.41-1}$ = 1.76

$\frac{T_2}{T_1}$ = 1.76 → $T_2 = T_1$ x 1.76 → 343 x 176

T_2 = 603.68 K

(iii) Temperature at the end of the heat addition

Q_A= m$\boldsymbol{C_v}$ (T_3 - T_2)

465 = 1 x 0.706 (T_3 - 603.68)

T_3 = 1262.32 K

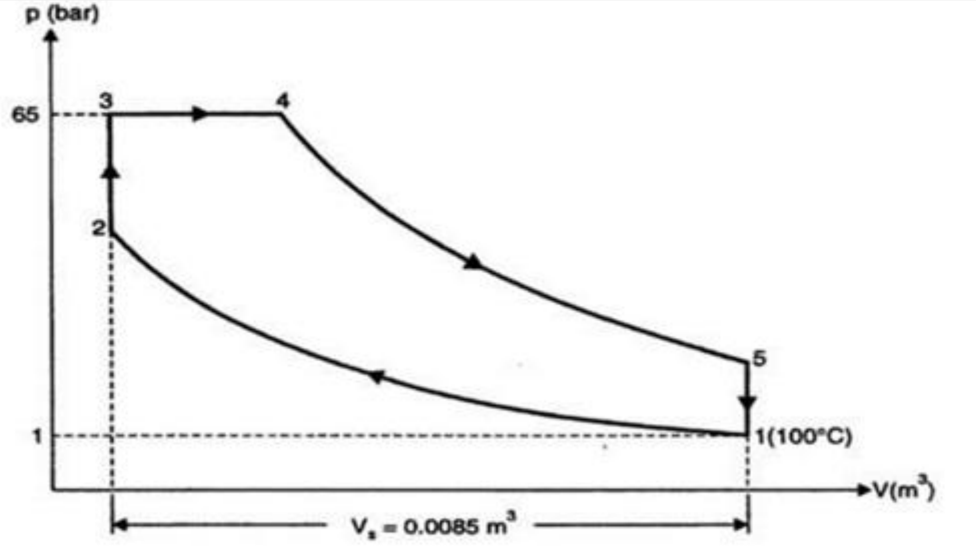
(iii) Temperature at the end of the heat addition

Q_A= m$\boldsymbol{C_v}$ (T_3 - T_2)

465 = 1 x 0.706 (T_3 - 603.68)

T_3 = 1262.32 K

2. A diesel engine working on a dual combustion cycle has a stroke volume of 0.0085 m^3 and a compression ratio 15:1. The fuel has a calorific value of 43890 kJ/kg. At the end of suction, the air is at 1 bar and 100^0C. The maximum pressure in the cycle is 65 bar and air fuel ratio is 21:1. Find for ideal cycle the thermal efficiency. Assume $C_p = 1.0$ kJ/kgK and C_v= 0.71 kJ/kgK.



Sol: T_1= 100 + 273 = 373 K

P_1= 1 bar

Maximum pressure in the cycle P_3 = P_4 = 65 bar

Stroke volume = 0.0085 m^3

Air fuel ratio = 21:1 ; Compression ratio = 15:1

Calorific value C = 43890 kJ/kg

C_p = 1.0 kJ/kgK ; C_v = 0.71 kJ/kgK

Thermal efficiency :

$V_s = V_1 - V_2 = 0.0085 \text{ m}^3$

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

$15V_2 - V_2 = 0.0085$

$14\, V_2 = 0.0085$

$V_2 = V_3 = V_c = \frac{0.0085}{14} = 0.0006 \text{ m}^3$

For adiabatic process 1-2

$P_1 {V_1}^{\gamma} = P_2 {V_2}^{\gamma}$

$P_2 = P_1 (\frac{V_1}{V_2})^{\gamma}$ = 1 X $(15^{1.41})$

γ = $\frac{C_p}{C_v} = \frac{1.0}{0.71}$ = 1.41

= 45.5 bar

Also, $\frac{T_2}{T_1}$ = $(\frac{V_1}{V_2})^{\gamma-1}$ = $r^{\gamma-1}$ = $15^{1.41-1}$= 3.04

Therefore T_2 = T1 x 3.04 = 373 x 3.04 = 1134 K or 861 ^0C

For constant volume process 2-3,

$\frac{P_2}{T_2} = \frac{P_3}{T_3}$;

or $T_3 = T_2$ x $\frac{P_3}{P_2}$ = 1134 x $\frac{65}{45.5}$ = 1620 K or 1347 ^0C

According to equation of gas

$P_1 V_1$ = mRT□1

m = $\frac{P_1 V_1}{RT1}$ = $\frac{1X10^5 X0.009}{287X373}$ = 0.0084 kg

Heat added during constant volume process 2-3

= m x $C_v (T_3 - T_2)$

= 0.0084 X 0.71(1630 – 1134)

=2.898 Kj

Amount of fuel added during the constant volume process 2-3,

= $\frac{2.898}{43890}$ = 0.000066 kg

Also as air-fuel ratio is 21:1

Therefore amount of fuel added = $\frac{0.0084}{21}$ = 0.0004 kg

Quantity of fuel added during the process 3-4,

= 0.0004 – 0.000066 = 0.000334 kg

Therefore heat added during the constant pressure operation 3-4

= 0.0000334 x 43890 = 14.66 Kj

But (0.0084 + 0.0004)$C_p(T_4 - T_3)$= 14.66

0.0088 X 1.0 (T_4 - 1620) = 14.66

T_4 = $\frac{14.66}{00088} + 1620 = 3286 = 3286\, K\; or\; 3013\,^0\, C$

Again for operation 3-4,

$$\frac{V_3}{T_3} = \frac{V_4}{T_4} \quad \text{or} \quad V_4 = \frac{V_3 T_4}{T_3} = \frac{0.0006\ X\ 2286}{1620} = 0.001217\ m^3$$

For adiabatic expansion operation 4-5;

$$\frac{T_4}{T_5} = (\frac{V_5}{V_4})^{\gamma-1} = (\frac{0.009}{0.001217})^{1.41-1} = 2.27$$

$$\text{or } T_5 = \frac{T_4}{2.27} = \frac{3286}{2.27} = 1447.5 \text{ or } 1174.5\ {}^0\text{C}$$

Heat rejected during constant volume process 5-1 = m$C_v(T_5 - T_1)$

= (0.00854 + 0.0004) X 0.71(1447.5 - 373) = 6.713kJ

Work dione = heat supplied – heat rejected = = (2.898 + 14.66)-6.713 = 10.845 Kj

Therefore thermal efficiency ,

$$\eta_{th} = \frac{work\ done}{heat\ supplied} = \frac{10.845}{2.898+14.86} = 0.6176 \text{ or } 61.76\%$$

3. In an air standard diesel cycle the compression ratio is 16, and at the beginning of the isentropic compression, the temperature is 15^0C and the pressure is 0.1MPa. Heat is added until the temperature at the end of the constant pressure is 1480^0C , calculate

(i) The cut off ratio

(ii) Heat supplied per kg of air

(iii) The cycle efficiency

(iv) The mean effective pressure

Sol: Compression Ratio (r) = 16
Initial temperature (T_1) = 15°C = 288 K
Initial pressure (P_1) = 0.1 MPa
Final temperature after heat addition (T_3) = 1480°C = 1753 K

The Diesel cycle consists of the following processes:

Isentropic compression: From T_1 to T_2.

Constant-pressure heat addition: From T_2 to T_3.

Isentropic expansion: From T_3 to T_4.

Constant-volume heat rejection: From T_4 back to T_1.

Cut-Off Ratio ($\boldsymbol{r_c}$)

$$\frac{T_2}{T_1} = r^{\gamma-1}$$

$$T_2 = T_1 r^{\gamma-1} = 288 \times 16^{0.4} = 873.05$$

$$\boldsymbol{r_c} = \frac{T_3}{T_2} = \frac{1732}{873.05} = 2.01$$

Heat Supplied per kg of Air (q_{in})

The heat added per kilogram of air during the constant-pressure process 2-3

$q_{in}=C_p\cdot(T3-T2)$

$q_{in}=1.005(1753-873.05) \approx 1.005 \times 879.95 \approx 884.35$ kJ/kg

So, the Heat Supplied per kg of Air $q_{in} \approx 884.35$ kJ/kg

Cycle Efficiency (η)

The efficiency of the Diesel cycle is given by:

$$\eta = 1- \frac{1}{r^{\gamma-1}} \text{ x } \frac{r_c^{\gamma}-1}{\gamma\,(r_{c\,-1})} = 1- \frac{1}{16^{0.4}}\ X\ \frac{2.65-1}{1.4\,(2.01-1)}\ 0.613$$

$\eta = 61.3\%$

Mean Effective Pressure (MEP)

$$\text{MEP} = \frac{\eta \ x \ q_{in}}{v(r-1)}$$

$$= \frac{0.613 \ x \ 884.35}{16-1} = 36.16 \text{ kPa}$$

3. In an engine working on dual cycle, the temperature and pressure at the beginning of the cycle are 90^0C and 1 bar respectively. The compression ratio is 9. The maximum pressure is limited to 68 bar and total heat supplied per kg of air is 1750 kJ. Determine:

(i) Pressure and temperature at all salient points

(ii) Air tandard efficiency

(iii) Mean effective pressure

Sol: $\mathrm{P_1} = 1\mathrm{bar}$

T_1 = 90+273 = 363 K

r = 9

$\mathrm{P_3} = \mathrm{P_4}$ = 68 bar ; Total heat supplied = 1750 kJ/kg

(i) Pressure and temperature at salient points:

For the isentropic process 1-2,

$P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$

$P_2 = P_1 \text{ X } (\frac{V_1}{V_2})^{\gamma} = 1 \text{ X } r^{\gamma} = 1 \text{ X } 9^{1.4} = 21.67 \text{ bar}$

Also, $\frac{T_2}{T_1} = (\frac{V_1}{V_2})^{\gamma-1} = (r)^{\gamma-1} = 9^{1.4-1} = 2.408$

$T_2 = T_1 \text{ X } 2.408 = 363 \text{ X } 2.408 = 874.1 \text{ K}$

$P_3 = P_4 = 68 \text{ bar}$

For the constant volume process 2-3,

$\frac{P_2}{T_2} = \frac{P_3}{T_3}$; $T_3 = T_2 \text{ x } \frac{P_3}{P_2} = 874.1 \text{ x } \frac{68}{21.67} = 2742.9 \text{ K}$

Heat added at constant volume = $C_p(\mathrm{T}_3 - \mathrm{T}_2)$ = 0.71 (2742.9 – 874.1) = 1326.8 kJ/kg

Heat added at constant pressure = Total heat added – Heat added at constant volume

= 1750 – 1326.8 = 423.2 kJ/kg

Therefore $C_p(\mathrm{T}_4 - \mathrm{T}_3)$ = 423.2

10 (T_4 - 2742.9) = 423.2

T_4 = 3166 K

For constant pressure process 3-4,

$$P = \frac{V_4}{V_3} = \frac{\mathrm{T}_4}{\mathrm{T}_3} = \frac{3166}{2742.9} = 1.15$$

For adiabatic (or isentropic) process 4-5,

$$\frac{V_5}{V_4} = \frac{V_5}{V_2} \times \frac{V_2}{V_4} = \frac{V_1}{V_2} \times \frac{V_3}{V_4} = \frac{r}{\rho}$$

Also $P_4 V_4^{\gamma} = P_5 V_5^{\gamma}$

$P_5 = P_4 \text{ X } (\frac{V_4}{V_5})^{\gamma} = 68 \text{ X } (\frac{\rho}{r})^{\gamma} = 68 \text{ x } (\frac{1.15}{9})^{1.4} = 3.81 \text{ bar}$

Again $\frac{T_5}{T_4} = (\frac{V_4}{V_5})^{\gamma-1} = (\frac{\rho}{r})^{\gamma-1} = (\frac{1.15}{9})^{1.4-1} = 0.439$

$T_5 = T_4 \text{ x } 0.439 = 3166 \text{ x } 0.439 = 1389.9 \text{ K}$

(ii) Air standard efficiency:

Heat rejected during constant volume process 5-1

$Q_r = C_v(T_5 - T_1) = 0.71(1389.8 – 363) = 729 \text{ kJ/kg}$

Therefore $\eta_{\text{air standard}} = \frac{\text{work done}}{\text{heat supplied}} = \frac{Q_s - Q_r}{Q_s} = \frac{1750-729}{1750} = 0.5834 \text{ or } 58.24\%$

(iii) Mean effective pressure p_m

$$p_m = \frac{\text{work done per cycle}}{\text{stroke volume}}$$

$$= \frac{1}{V_s} [\ P_2\ (V_4\ -\ V_3) + \frac{P_4V_4 - P_5V_5}{\gamma - 1} - \frac{P_{c2}V_2 - P_1V_1}{\gamma - 1}$$

$V_1 = V_5 =$ r V_c ; $V_2 = V_3 = V_c$; $V_4 = \rho\ V_c$

$V_s = (r-1)\ V_c$ since r $= \frac{V_s + V_c}{V_c} = 1 + \frac{V_s}{V_c}$

Therefore $V_s = (r - 1)\ V_c$

$$p_m = \frac{1}{(r-1)V_c} [P_3(\rho\ V_c - V_c) + \frac{P_4 \rho V_c - P_5 r V_c}{\gamma - 1} - \frac{P_2 V_c - P_2 r V_c}{\gamma - 1}]$$

R = 9 , ρ = 1.15 , γ =1.4

P_1 = 1bar, P_2 =21.67 bar ,

$$\therefore \quad p_m = \frac{1}{(r-1)V_c}\left[p_3(\rho V_c - V_c) + \frac{p_4\rho V_c - p_5 \times rV_c}{\gamma - 1} - \frac{p_2V_c - p_1rV_c}{\gamma - 1}\right]$$

$r = 9, \rho = 1.15, \gamma = 1.4$

$p_1 = 1$ bar, $p_2 = 21.67$ bar, $p_3 = p_4 = 68$ bar, $p_5 = 3.81$ bar

Substituting the above values in the above equation, we get

$$p_m = \frac{1}{(9-1)}\left[68(1.15-1) + \frac{68 \times 1.15 - 3.81 \times 9}{1.4 - 1} - \frac{21.67 - 9}{1.4 - 1}\right]$$

$$= \frac{1}{8}(10.2 + 109.77 - 31.67) = 11.04 \text{ bar}$$

Hence, *mean effective pressure* = **11.04 bar. (Ans.)**

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Course Title	**ENGINEERING THERMODYNAMICS**
Course Code	**AMED07**
Class	**III SEM**
Section	**A**
Name of the Faculty	**Dr G.Hima Bindu**
Lecture hour and Date	
Course Outcome/s	
Topic covered	
Topic learning outcome	

OUTCOMES: Determine heat, work, internal energy, enthalpy for flow & non flow process using First Law of Thermodynamics.

Example 3.30. *(a) With the help of p-v and T-s diagram compare the cold air standard otto, diesel and dual combustion cycles for same maximum pressure and maximum temperature.* **(AMIE Summer, 1998)**

Solution. Refer Fig. 3.29. (*a*, *b*).

The air-standard Otto, Dual and Diesel cycles are drawn on common p-v and T-s diagrams for the same maximum pressure and maximum temperature, for the purpose of comparison.

Otto 1-2-3-4-1, Dual 1-2′-3′-3-4-1, Diesel 1-2″-3-4-1 (Fig 3.29 (*a*)).

Slope of constant volume lines on T-s diagram is higher than that of constant pressure lines. (Fig. 3.29 (*b*)).

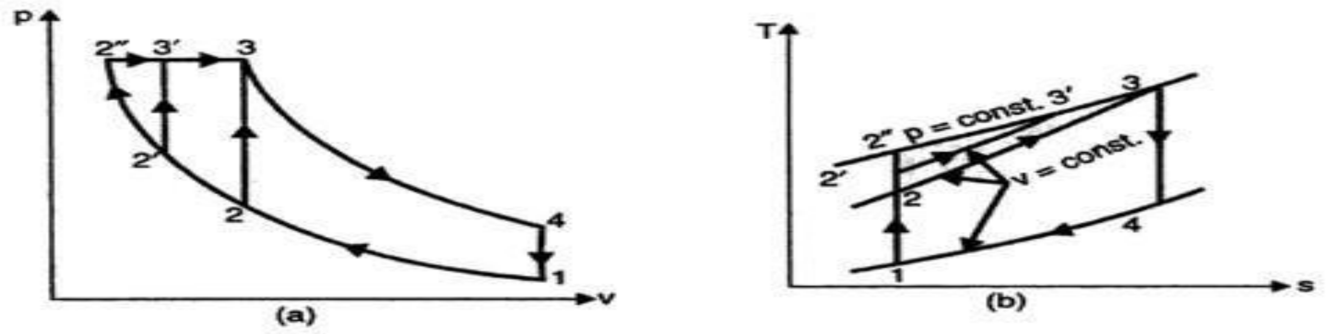


Fig. 3.29

Here the otto cycle must be limited to a low compression ratio (r) to fulfill the condition that point 3 (same maximum pressure and temperature) is to be a common state for all the three cycles.

The construction of cycles on T-s diagram proves that for the given conditions the heat rejected is same for all the three cycles (area under process line 4-1). Since, by definition,

$$\eta = 1 - \frac{\text{Heat rejected, } Q_r}{\text{Heat supplied, } Q_s} = 1 - \frac{\text{Const.}}{Q_s}$$

the cycle, with greater heat addition will be more efficient. From the T-s diagram,

$$Q_{s(\text{diesel})} = \text{Area under 2″-3}$$

$$Q_{s(\text{dual})} = \text{Area under 2′-3′-3}$$

$$Q_{s(\text{otto})} = \text{Area under 2-3.}$$

It can be seem that, $Q_{s(\text{diesel})} > Q_{s(\text{dual})} > Q_{s(\text{otto})}$

and thus, $\eta_{\text{diesel}} > \eta_{\text{dual}} > \eta_{\text{otto}}$.

In an engine working on Dual cycle, the temperature and pressure at the beginning of the cycle are 90°C and 1 bar respectively. The compression ratio is 9. The maximum pressure is limited to 68 bar and total heat supplied per kg of air is 1750 kJ. Determine :

(*i*) *Pressure and temperatures at all salient points*

(*ii*) *Air standard efficiency*

(*iii*) *Mean effective pressure.*

Solution. Refer Fig. 3.22.

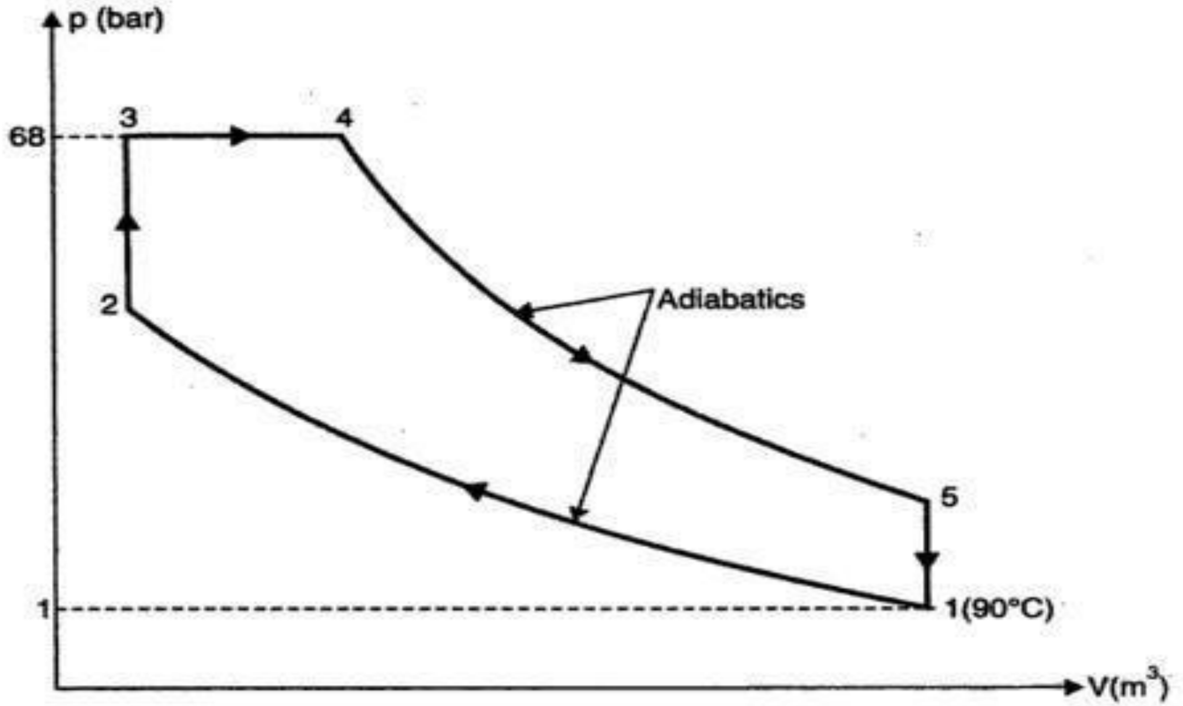


Fig. 3.22

Initial pressure, $p_1 = 1$ bar

Initial temperature, $T_1 = 90 + 273 = 363$ K

Compression ratio, $r = 9$

Maximum pressure, $p_3 = p_4 = 68$ bar

Total heat supplied $= 1750$ kJ/kg

(*i*) **Pressures and temperatures at salient points :**

For the *isentropic process* 1-2,

$$p_1V_1^{\gamma} = p_2V_2^{\gamma}$$

$$\mathbf{p_2} = p_1 \times \left(\frac{V_1}{V_2}\right)^{\gamma} = 1 \times (r)^{\gamma} = 1 \times (9)^{1.4} = \mathbf{21.67\ bar.} \quad \textbf{(Ans.)}$$

Also,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r)^{\gamma-1} = (9)^{1.4-1} = 2.408$$

$\therefore$

$$\mathbf{T_2} = T_1 \times 2.408 = 363 \times 2.408 = \mathbf{874.1\ K.} \quad \textbf{(Ans.)}$$

$$\mathbf{p_3 = p_4 = 68\ bar.} \quad \textbf{(Ans.)}$$

For the *constant volume process* 2-3,

$$\frac{p_2}{T_2} = \frac{p_3}{T_3}$$

$$\therefore \quad \mathbf{T_3} = T_2 \times \frac{p_3}{p_2} = 874.1 \times \frac{68}{21.67} = \mathbf{2742.9\ K.} \quad \textbf{(Ans.)}$$

Heat added at constant volume

$$= c_v (T_3 - T_2) = 0.71\ (2742.9 - 874.1) = 1326.8 \text{ kJ/kg}$$

$\therefore$ **Heat added at constant pressure**

$$= \text{Total heat added} - \text{Heat added at constant volume}$$

$$= 1750 - 1326.8 = 423.2 \text{ kJ/kg}$$

$$\therefore \quad c_p(T_4 - T_3) = 423.2$$

$$1.0(T_4 - 2742.9) = 423.2$$

$$\therefore \quad \mathbf{T_4} = \mathbf{3166\ K.} \quad \textbf{(Ans.)}$$

For *constant pressure process* 3-4,

$$\rho = \frac{V_4}{V_3} = \frac{T_4}{T_3} = \frac{3166}{2742.9} = 1.15$$

For *adiabatic (or isentropic) process* 4-5,

$$\frac{V_5}{V_4} = \frac{V_5}{V_2} \times \frac{V_2}{V_4} = \frac{V_1}{V_2} \times \frac{V_3}{V_4} = \frac{r}{\rho} \qquad \left(\because \ \rho = \frac{V_4}{V_3}\right)$$

Also $\quad p_4 V_4^{\gamma} = p_5 V_5^{\gamma}$

$$\therefore \quad \mathbf{p_5} = p_4 \times \left(\frac{V_4}{V_5}\right)^{\gamma} = 68 \times \left(\frac{\rho}{r}\right)^{\gamma} = 68 \times \left(\frac{1.15}{9}\right)^{1.4} = \mathbf{3.81\ bar.} \quad \textbf{(Ans.)}$$

Again, $\quad \dfrac{T_5}{T_4} = \left(\dfrac{V_4}{V_5}\right)^{\gamma-1} = \left(\dfrac{\rho}{r}\right)^{\gamma-1} = \left(\dfrac{1.15}{9}\right)^{1.4-1} = 0.439$

$$\therefore \quad \mathbf{T_5} = T_4 \times 0.439 = 3166 \times 0.439 = \mathbf{1389.8\ K.} \quad \textbf{(Ans.)}$$

(*ii*) **Air standard efficiency :**

Heat rejected during constant volume process 5-1,

$$Q_r = C_v(T_5 - T_1) = 0.71(1389.8 - 363) = 729 \text{ kJ/kg}$$

$$\therefore \qquad \eta_{\text{air-standard}} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{Q_s - Q_r}{Q_s}$$

$$= \frac{1750 - 729}{1750} = \mathbf{0.5834 \text{ or } 58.34\%.} \quad \textbf{(Ans.)}$$

(*iii*) **Mean effective pressure, p_m :**

Mean effective pressure is given by

$$p_m = \frac{\text{Work done per cycle}}{\text{Stroke volume}}$$

$$p_m = \frac{1}{V_s}\left[p_3(V_4 - V_3) + \frac{p_4V_4 - p_5V_5}{\gamma - 1} - \frac{p_2V_2 - p_1V_1}{\gamma - 1}\right]$$

$$V_1 = V_5 = r\,V_c,\ V_2 = V_3 = V_c,\ V_4 = \rho V_c, \qquad \left[\because \quad r = \frac{V_s + V_c}{V_c} = 1 + \frac{V_s}{V_c}\right.$$

$$V_s = (r - 1)\,V_c \qquad\qquad \left.\therefore \ V_s = (r-1)V_c\right]$$

$$\therefore \qquad p_m = \frac{1}{(r-1)V_c}\left[p_3(\rho V_c - V_c) + \frac{p_4\rho V_c - p_5 \times rV_c}{\gamma - 1} - \frac{p_2 V_c - p_1 rV_c}{\gamma - 1}\right]$$

$$r = 9,\ \rho = 1.15,\ \gamma = 1.4$$

$$p_1 = 1 \text{ bar},\ p_2 = 21.67 \text{ bar},\ p_3 = p_4 = 68 \text{ bar},\ p_5 = 3.81 \text{ bar}$$

Substituting the above values in the above equation, we get

$$p_m = \frac{1}{(9-1)}\left[68(1.15-1) + \frac{68 \times 1.15 - 3.81 \times 9}{1.4 - 1} - \frac{21.67 - 9}{1.4 - 1}\right]$$

$$= \frac{1}{8}(10.2 + 109.77 - 31.67) = 11.04 \text{ bar}$$

Hence, ***mean effective pressure*** **= 11.04 bar. (Ans.)**

A Diesel engine working on a dual combustion cycle has a stroke volume of 0.0085 m^3 and a compression ratio 15 : 1. The fuel has a calorific value of 43890 kJ/kg. At the end of suction, the air is at 1 bar and 100°C. The maximum pressure in the cycle is 65 bar and air fuel ratio is 21 : 1. Find for ideal cycle the thermal efficiency. Assume c_p = 1.0 kJ/kg K and c_v = 0.71 kJ/kg K.

Solution. Refer Fig. 3.24.

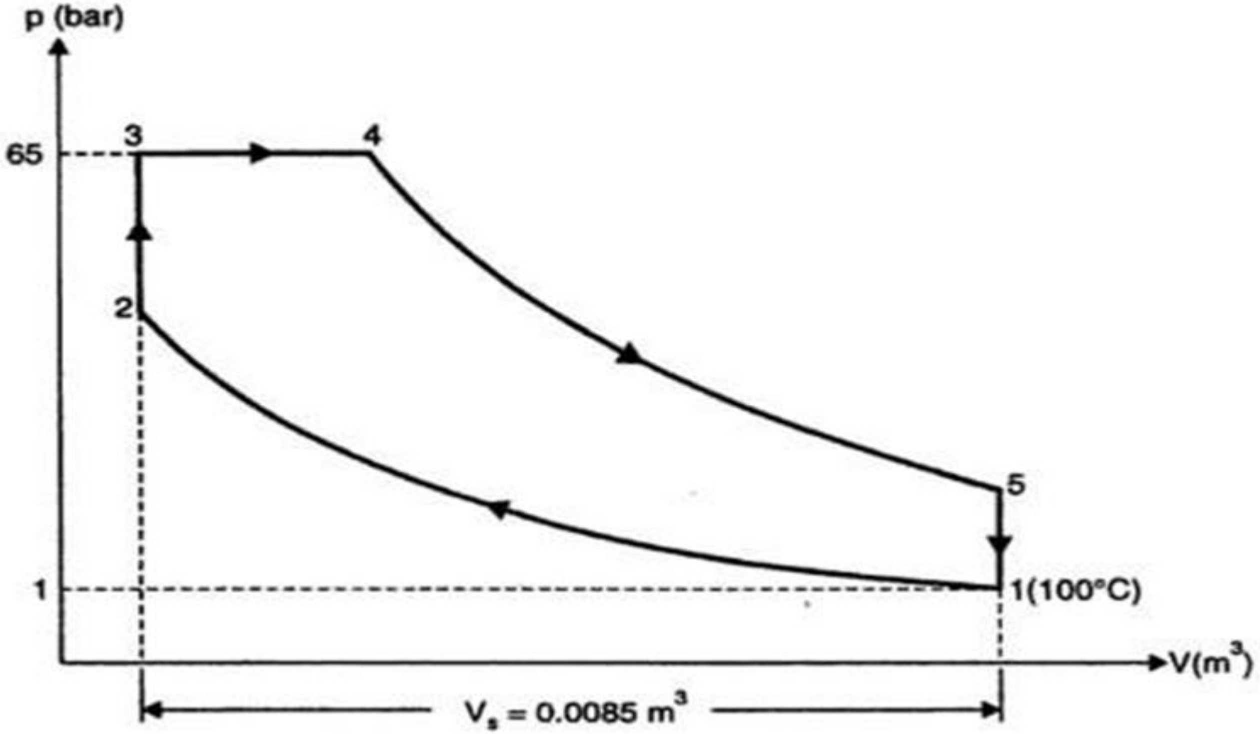


Fig. 3.24

Initial temperature, $T_1 = 100 + 273 = 373$ K

Initial pressure, $p_1 = 1$ bar

Maximum pressure in the cycle, $p_3 = p_4 = 65$ bar

Stroke volume, $V_s = 0.0085 \text{ m}^3$

Air-fuel ratio $= 21 : 1$

Compression ratio, $r = 15 : 1$

Calorific value of fuel, $C = 43890$ kJ/kg

$c_p = 1.0$ kJ/kg K, $c_v = 0.71$ kJ/kg K

Thermal efficiency :

$$V_s = V_1 - V_2 = 0.0085 \text{ m}^3$$

and as $$r = \frac{V_1}{V_2} = 15, \text{ then } V_1 = 15V_2$$

$\therefore$ $$15V_2 - V_2 = 0.0085$$

or $$14V_2 = 0.0085$$

or $$V_2 = V_3 = V_c = \frac{0.0085}{14} = 0.0006 \text{ m}^3$$

For *adiabatic compression process 1-2,*

$$p_1V_1^{\gamma} = p_2V_2^{\gamma}$$

or $$p_2 = p_1 \cdot \left(\frac{V_1}{V_2}\right)^{\gamma} = 1 \times (15)^{1.41} \qquad \left[\gamma = \frac{c_p}{c_v} = \frac{1.0}{0.71} = 1.41\right]$$

$$= 45.5 \text{ bar}$$

Also, $$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r)^{\gamma-1} = (15)^{1.41-1} = 3.04$$

$\therefore$ $$T_2 = T_1 \times 3.04 = 373 \times 3.04 = 1134 \text{ K or } 861°\text{C}$$

For *constant volume process 2-3,*

$$\frac{p_2}{T_2} = \frac{p_3}{T_3}$$

or $$T_3 = T_2 \times \frac{p_3}{p_2} = 1134 \times \frac{65}{45.5} = 1620 \text{ K or } 1347°\text{C}$$

According to characteristic equation of gas,

$$p_1V_1 = mRT_1$$

$\therefore$ $$m = \frac{p_1V_1}{RT_1} = \frac{1 \times 10^5 \times 0.009}{287 \times 373} = 0.0084 \text{ kg (air)}$$

Heat added during constant volume process 2-3,

$$= m \times c_v (T_3 - T_2)$$

$$= 0.0084 \times 0.71 (1620 - 1134)$$

$$= 2.898 \text{ kJ}$$

Amount of fuel added during the *constant volume process 2-3,*

$$= \frac{2.898}{43890} = 0.000066 \text{ kg}$$

Also as air-fuel ratio is 21 : 1.

$\therefore$ Total amount of fuel added $= \dfrac{0.0084}{21} = 0.0004$ kg

Quantity of fuel added during the process 3-4,

$$= 0.0004 - 0.000066 = 0.000334 \text{ kg}$$

$\therefore$ *Heat added during the constant pressure operation 3-4*

$$= 0.000334 \times 43890 = 14.66 \text{ kJ}$$

But $(0.0084 + 0.0004)\, c_p\, (T_4 - T_3) = 14.66$

$$0.0088 \times 1.0\, (T_4 - 1620) = 14.66$$

$$\therefore \quad T_4 = \frac{14.66}{0.0088} + 1620 = 3286 \text{ K or } 3013°\text{C}$$

Again for operation 3-4,

$$\frac{V_3}{T_3} = \frac{V_4}{T_4} \quad \text{or} \quad V_4 = \frac{V_3 T_4}{T_3} = \frac{0.0006 \times 3286}{1620} = 0.001217 \text{ m}^3$$

For adiabatic expansion operation 4-5,

$$\frac{T_4}{T_5} = \left(\frac{V_5}{V_4}\right)^{\gamma - 1} = \left(\frac{0.009}{0.001217}\right)^{1.41-1} = 2.27$$

or

$$T_5 = \frac{T_4}{2.27} = \frac{3286}{2.27} = 1447.5 \text{ K or } 1174.5°\text{C}$$

Heat rejected during constant volume process 5-1,

$$= m\, c_v\, (T_5 - T_1)$$

$$= (0.00854 + 0.0004) \times 0.71\, (1447.5 - 373) = 6.713 \text{ kJ}$$

Work done = Heat supplied – Heat rejected

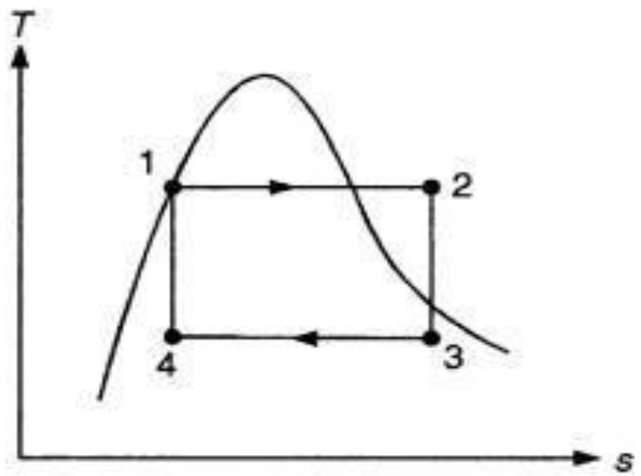
$$= (2.898 + 14.66) - 6.713 = 10.845 \text{ kJ}$$

∴ *Thermal efficiency,*

$$\eta_{th} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{10.845}{(2.898 + 14.66)} = \mathbf{0.6176 \text{ or } 61.76\%}. \quad \textbf{(Ans.)}$$

EXAMPLE 9.1

A steam power plant operates between a boiler pressure of 4 MPa and 300°C and a condenser pressure of 50 kPa. Determine the thermal efficiency of the cycle, the work ratio, and the specific steam flow rate, assuming (a) the cycle to be a Carnot cycle, and (b) a simple ideal Rankine cycle.



Solution

(a) The T–s diagram of a Carnot cycle is shown in the adjacent figure.

Process 1–2 is reversible and isothermal heating of water in the boiler.

Process 2–3 is isentropic expansion of steam at state 2 in the turbine.

Process 3–4 is reversible and isothermal condensation of steam in the condenser.

Process 4–1 is isentropic compression of steam to initial state.

At state 1: $P_1 = 4$ MPa, $T_1 = 300°C$

At state 2: $P_2 = 50$ kPa, the steam is in a saturated state.

From the saturated water-pressure table (Table 4 of the Appendix), at 50 kPa, we get $T_2 = T_{min} = T_{sat} = 81.33°C$

Δpe of the steam are usually small compared with the work and heat transfer terms and are, therefore, neglected. Thus, the steady-flow energy equation per unit mass of steam is

$$q - w = h_e - h_i \quad \text{(kJ/kg)} \tag{9.1}$$

Assuming the pump and turbine to be isentropic and noting that there is no work associated with the boiler and the condenser, the energy conservation relation for each device becomes

$$w_{\text{pump,in}} = h_2 - h_1 = v(P_2 - P_1) \tag{9.2}$$

$$q_{\text{boi,in}} = h_3 - h_2 \tag{9.3}$$

$$w_{\text{turb,out}} = h_3 - h_4 \tag{9.4}$$

$$q_{\text{cond,out}} = h_4 - h_1 \tag{9.5}$$

The thermal efficiency of the Rankine cycle is given by

$$\boxed{\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}} \tag{9.6}$$

where $w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = w_{\text{turb,out}} - w_{\text{pump,in}}$

The η_{th} can also be interpreted as the ratio of the area enclosed by the cycle on a T–s diagram to the area under the heat addition process.

Therefore, the thermal efficiency for the given Carnot cycle is

$$\eta_{th,carnot} = 1 - \frac{T_{min}}{T_{max}} = 1 - \frac{81.33 + 273.15}{300 + 273.15} = 0.3815$$

$$= \boxed{38.15 \text{ per cent}}$$

The work ratio $= \dfrac{\text{net work output}}{\text{gross work output}} = \dfrac{w_{net,out}}{w_{gross,out}}$

Heat supplied $= h_2 - h_1 = h_{fg\,@\,4MPa} = 1714.1$ kJ/kg (From Table 4 of the Appendix)

$$\eta_{th,carnot} = \frac{w_{net,out} - w_{net,in}}{\text{gross heat supplied}} = 0.3815$$

Therefore,

$$w_{net,\,out} - w_{net,\,in} = 0.3815 \times 1714.1 = 653.9 \text{ kJ/kg}$$

That is, the net work output = 653.9 kJ/kg.

To find the expansion work for the process 2–3, h_3 is required.

From Table 4, $h_2 = 2801.4$ kJ/kg and $s_2 = s_3 = 6.0701$ kJ/(kg K)

But $$s_3 = 6.0701 = s_{f3} + x_3 s_{fg3} = 1.0910 + x_3(7.5939 - 1.0910)$$

or

$$x_3 = 0.766$$

Now,

$$h_3 = h_{f3} + x_3 h_{fg3} = 340.49 + 0.766(2645.9 - 340.49) = 2106.4 \text{ kJ/kg}$$

Therefore,

$$w_{32} = h_2 - h_3 = 2801.4 - 2106.4 = 695 \text{ kJ/kg}$$

That is, the gross work output, $w_{gross,out} = 695$ kJ/kg
Therefore,

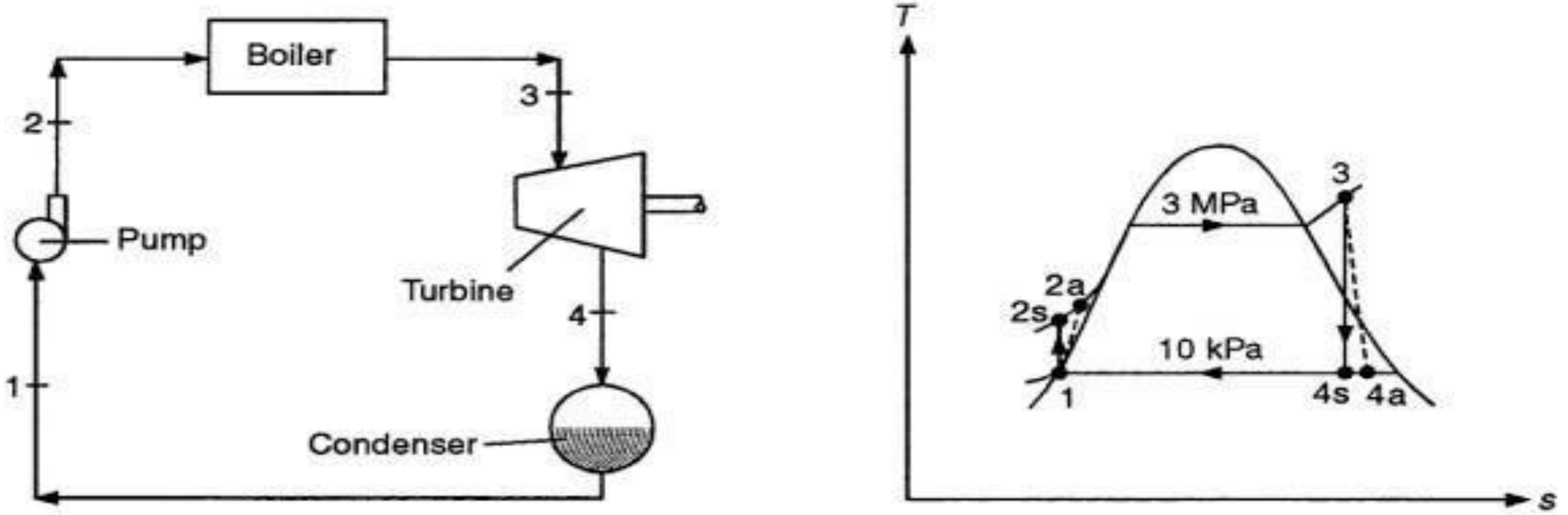
$$\text{Work ratio} = \frac{w_{net,out}}{w_{gross,out}} = \frac{653.9}{695} = \boxed{0.94}$$

The specific steam flow rate (ssfr) is the steam flow required to develop unit power output. That is,

$$\text{ssfr} = \frac{\dot{m}_{steam}}{\dot{m}_s w_{out}} = \frac{1}{w_{net,\,out}}$$

$$= \frac{1}{653.9} = \boxed{0.00153 \text{ kg/kW}}$$

A steam power plant operates on the cycle shown below with 3 MPa and 400°C at the turbine inlet and 10 kPa at the turbine exhaust. The adiabatic efficiency of the turbine is 85 per cent and that of the pump is 80 per cent. Determine (a) the thermal efficiency of the cycle, and (b) the mass flow rate of the steam if the power output is 20 MW.



Solution

All the components are treated as steady-flow devices. The changes, if any, in the kinetic and potential energies are assumed to be negligible. Losses other than those in the turbine and pump are neglected.

(a) $$w_{\text{pump,in}} = \frac{v_1(P_2 - P_1)}{\eta_P} = \frac{0.001010\,(3000 - 10)}{0.80} = 3.77 \text{ kJ/kg}$$

Turbine work output is

$$w_{turb,out} = \eta_T w_{turb,in} = \eta_T (h_3 - h_{4s})$$

$$= 0.85(3230.90 - 2192.21) = 882.89 \text{ kJ/kg}$$

Boiler heat input is

$$q_{in} = h_3 - h_2 = 3230.9 - 195.59 = 3035.31 \text{ kJ/kg}$$

Thus,

$$w_{net,out} = w_{turb,out} - w_{pump,in} = 882.89 - 3.77 = 879.12 \text{ kJ/kg}$$

$$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{879.12}{3035.31} = 0.2896 = \boxed{28.96 \text{ per cent}}$$

If there are no losses in the turbine and the pump, the thermal efficiency would be 28.99 per cent.

(b) The power generated by the power plant is

$$\dot{W}_{net,out} = \dot{m} w_{net,out} = 20{,}000 \text{ kW}$$

Therefore, the mass flow rate, $\dot{m} = \dfrac{20{,}000}{879.12} = \boxed{22.75 \text{ kg/s}}$