INTERNAL COMBUSTION ENGINE

Module – IV

Working cycle:
(a) Otto cycle- thermodynamic cycle for SI/petrol engine

-Reversible adiabatic compression and expansion process
-Constant volume heat addition (combustion) and heat rejection process (exhaust)
Figure 7 depicts the Otto cycle

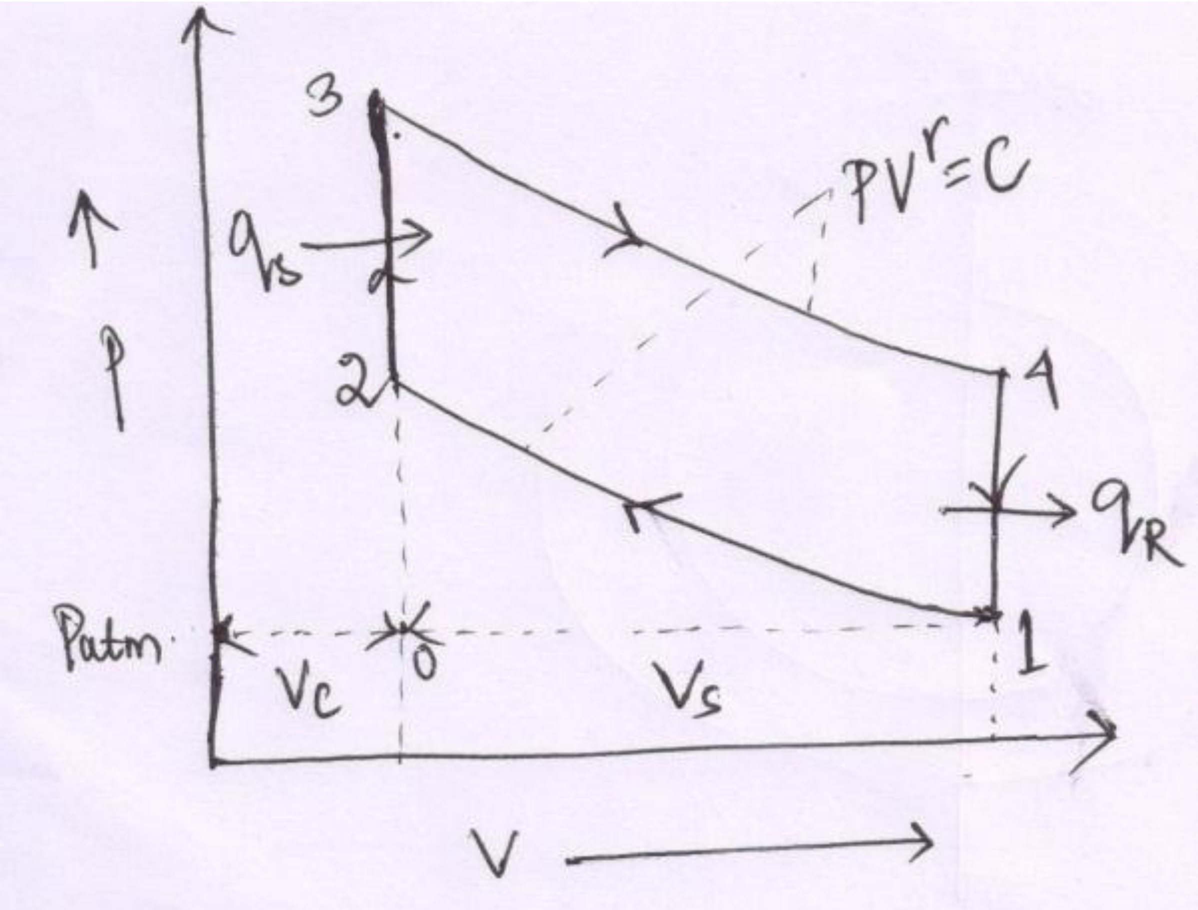

Fig. 7. Otto cycle

Heat supplied, $q_S=C_V(T_3-T_2)$
Heat rejection, $q_R=C_V(T_4-T_1)$

Compression ratio, $r_k = \frac{V_1}{V_2}$

Thermal efficiency, $\eta_{th} = \frac{q_s - q_R}{q_s} = \frac{Cv(T3-T2)-Cv(T4-T1)}{Cv(T3-T2)} = 1 - \frac{T4-T1}{T3-T2}$

In process 1-2, adiabatic compression process,

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

$$=> T_2 = T_1.(r_k)^{\gamma-1}$$

In adiabatic expansion process, i.e. 3-4,

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$=> T_3 = T_4.(r_k)^{\gamma-1}$$

$$\eta_{th} = 1 - \frac{T_4 - T_1}{T_4.(r_k)^{\gamma-1} - T_1.(r_k)^{\gamma-1}}$$

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

Work done (W)

Pressure ratio, $r_p = \frac{P_3}{P_2} = \frac{P_4}{P_1}$

$$\frac{P_2}{P_1} = \frac{P_3}{P_4} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r_k)^{\gamma}$$

$$W = \frac{P_3V_3 - P_4V_4}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$

$$= \frac{1}{\gamma - 1}\left[P_4V_4\left(\frac{P_3V_3}{P_4V_4} - 1\right) - P_1V_1\left(\frac{P_2V_2}{P_1V_1} - 1\right)\right]$$

$$= \frac{1}{\gamma - 1}[P_4V_1(r_k{}^{\gamma-1} - 1) - P_1V_1(r_k{}^{\gamma-1} - 1)]$$

$$= \frac{P_1V_1}{\gamma - 1}[r_p(r_k{}^{\gamma-1} - 1) - (r_k{}^{\gamma-1} - 1)]$$

$$= \frac{P_1V_1}{\gamma - 1}[(r_k{}^{\gamma-1} - 1)(r_p - 1)]$$

Mean effective pressure, $P_m = \frac{work\ done}{Swept\ volume} = \frac{work\ done}{V_1 - V_2}$

P_1V_1

$$P_m = \frac{\frac{P_1 V_1}{\gamma - 1}\left[(r_k^{\gamma-1} - 1)(r_p - 1)\right]}{V_1 - V_2} = \frac{P_1 r_k\left[(r_k^{\gamma-1} - 1)(r_p - 1)\right]}{(\gamma - 1)(r_k - 1)}$$

(b) ***Diesel cycle-*** thermodynamic cycle for low speed CI/diesel engine

-Reversible adiabatic compression and expansion process

-Constant pressure heat addition (combustion) and heat rejection process (exhaust)

Figure 8 depicts the diesel cycle.

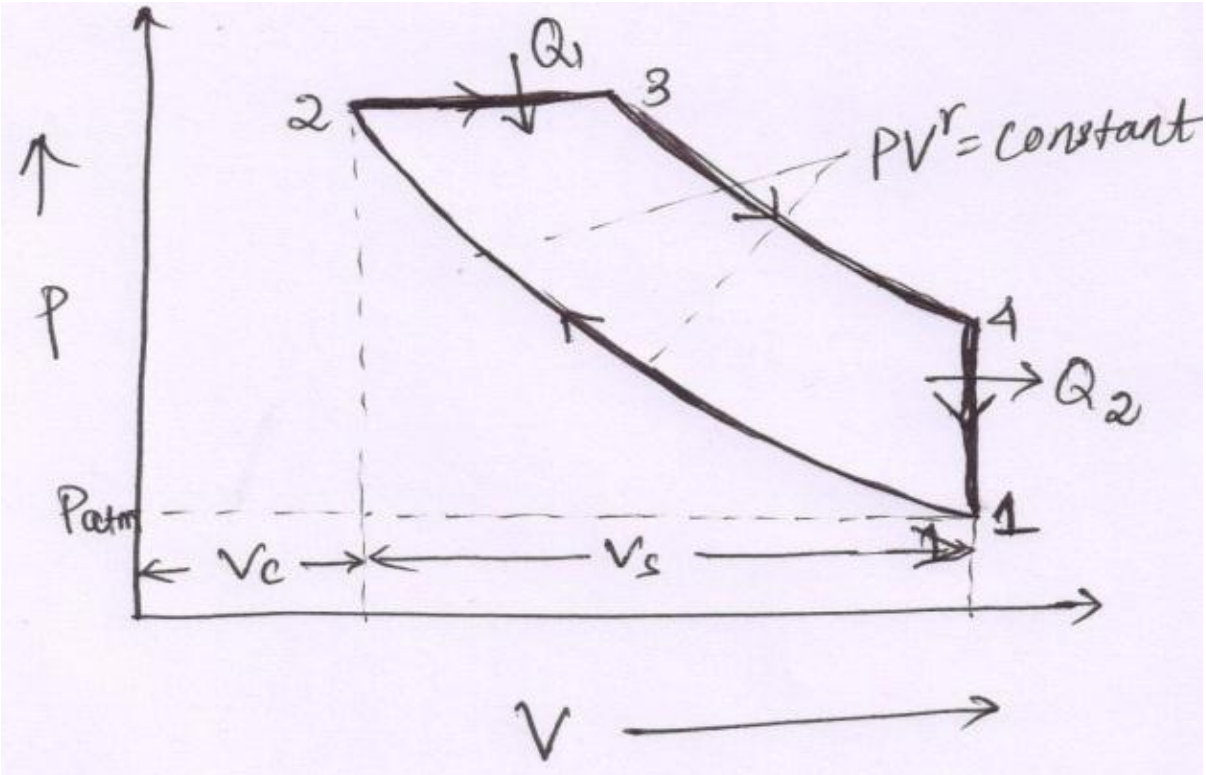

Fig. 8. Diesel cycle

Heat supplied, $Q_1=C_p(T_3-T_2)$
Heat rejection, $Q_2=C_v(T_4-T_1)$
Compression ratio, $r_k=\frac{V_1}{V_2}$

Cut off ratio, $r_c=\frac{V_3}{V_2}$

Thermal efficiency, $\eta_{th}=\frac{Q_1-Q_2}{Q_1}=\frac{C_p(T_3-T_2)-C_v(T_4-T_1)}{C_p(T_3-T_2)}=1-\frac{1}{\gamma}\frac{(T_4-T_1)}{(T_3-T_2)}$

In adiabatic compression process i.e. 1-2,

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

$$=> T_2=T_1.(r_k)^{\gamma-1}$$

In process 2-3, pressure constant, then

$$\frac{T_3}{T_2}=\frac{V_3}{V_2}=r_c$$

$$=> T_3=T_2.r_c=T_1.(r_k)^{\gamma-1}.r_c$$

In adiabatic expansion process i.e. 3-4,

$$\frac{T_4}{T_3}=\left(\frac{V_3}{V_4}\right)^{\gamma-1}=\left(\frac{V_3}{V_2}*\frac{V_2}{V_4}\right)^{\gamma-1}=(r_c)^{\gamma-1}*\frac{1}{(r_k)^{\gamma-1}}$$

$$=> T_4=T_3.(r_c)^{\gamma-1}*\frac{1}{(r_k)^{\gamma-1}}=T_1.(r_k)^{\gamma-1}.r_c.(r_c)^{\gamma-1}*\frac{1}{(r_k)^{\gamma-1}}=T_1.r_c$$

$$\eta_{th}=1-\frac{1}{\gamma}\frac{(T_4-T_1)}{(T_3-T_2)}=1-\frac{1}{\gamma.(r_k)^{\gamma-1}}\left[\frac{(r_c)^{\gamma}-1}{r_c-1}\right]$$

Work done (W)

$$W=P_2(V_3-V_2)+\frac{P_3V_3-P_4V_4}{\gamma-1}-\frac{P_2V_2-P_1V_1}{\gamma-1}$$

$$=P_2(r_cV_2-V_2)+\frac{P_2r_cV_2-P_4r_kV_2}{\gamma-1}-\frac{P_2V_2-P_1r_kV_2}{\gamma-1}$$ since $V_4=V_1$

$$=P_2V_2\left[\frac{(r_c-1)(\gamma-1)+(r_c-r_c{}^{\gamma}.r_k{}^{-\gamma}.r_k)-(1-r_k{}^{1-\gamma})}{\gamma-1}\right]$$

$$=P_1V_1.r_k{}^{\gamma-1}\left[\frac{\gamma(r_c-1)-r_k{}^{1-\gamma}(r_c{}^{\gamma}-1)}{\gamma-1}\right]$$

Mean effective pressure,

$$P_m = \frac{P_1 V_1 r_k^{\gamma-1}\left[\frac{\gamma(r_c-1)-r_k^{1-\gamma}(r_c^{\gamma}-1)}{\gamma-1}\right]}{V_1-V_2} = \frac{P_1 r_k^{\gamma}\left[\gamma(r_c-1)-r_k^{1-\gamma}(r_c^{\gamma}-1)\right]}{(\gamma-1)(r_k-1)}$$

(c) Dual cycle or limited pressure cycle-thermodynamic cycle for high speed diesel and hot spot ignition engine

-Reversible adiabatic compression and expansion process

-Constant pressure and constant volume heat addition (combustion) and heat rejection process

Total heat supplied, $Q_1 = C_v(T_3-T_2) + C_p(T_4-T_3)$

Heat rejection, $Q_2 = C_v(T_5-T_1)$

Compression ratio, $r_k = \frac{V_1}{V_2}$

Cut off ratio, $r_c = \frac{V_4}{V_3}$

Pressure ratio, $r_p = \frac{P_3}{P_2}$

Figure 9 shows the P-V diagram of Dual cycle.

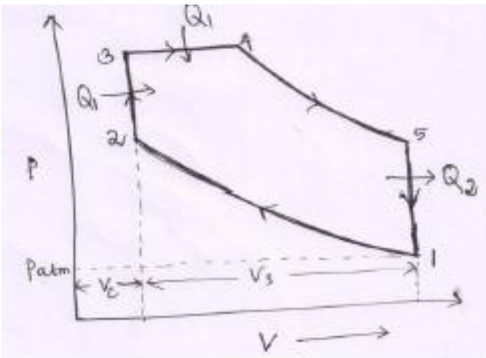

Fig. 9. Dual cycle

Thermal efficiency, $\eta_{th} = \frac{Q_1-Q_2}{Q_1} = \frac{C_v(T_3-T_2)+C_p(T_4-T_3)-C_v(T_5-T_1)}{C_v(T_3-T_2)+C_p(T_4-T_3)} = 1 - \frac{(T_5-T_1)}{(T_3-T_2)+\gamma(T_4-T_3)}$

In adiabatic compression process i.e. 1-2,

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

In constant volume combustion process i.e. 2-3,

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

$$=> T_2 = \frac{T_3}{r_p}$$

In constant pressure combustion process i.e. 3-4,

$\frac{V_3}{V_4} = \frac{T_3}{T_4}$

$$=> T_4 = T_3 . r_c$$

In adiabatic expansion process i.e. 4-5,

$$\frac{T_4}{T_5} = \left(\frac{V_5}{V_4}\right)^{\gamma-1} = \left(\frac{V_1}{V_4}\right)^{\gamma-1} = \left(\frac{r_k}{r_c}\right)^{\gamma-1}$$

$$=> T_5 = r_c * T_3 * \left(\frac{r_c}{r_k}\right)^{\gamma-1}$$

$$\eta_{th} = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)} = 1 - \frac{1}{(r_k)^{\gamma-1}}\left[\frac{r_p.(r_c)^{\gamma} - 1}{(r_p - 1) + \gamma r_p (r_c - 1)}\right]$$

<u>Work done (W)</u>

$$W = P_3(V_4 - V_3) + \frac{P_4V_4 - P_5V_5}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$

$$= P_3V_3(r_c - 1) + \frac{(P_4r_cV_3 - P_5r_kV_3) - (P_2V_3 - P_1r_kV_3)}{\gamma - 1}$$

$$= \frac{P_1V_1 . r_k{}^{\gamma-1}[\gamma r_p(r_c - 1) + (r_p - 1) - . r_k{}^{\gamma-1}(r_p r_c{}^{\gamma} - 1)]}{\gamma - 1}$$

Mean effective pressure,

$$P_m = \frac{\frac{P_1V_1.r_k^{\gamma-1}[\gamma r_p(r_c-1)+(r_p-1)-.r_k^{\gamma-1}(r_pr_c^{\gamma}-1)]}{\gamma-1}}{V_1-V_2}$$

$$= \frac{P_1r_k^{\gamma}[r_p(r_c-1)+(r_p-1)-.r_k^{1-\gamma}(r_pr_c^{\gamma}-1)]}{(\gamma-1)(r_k-1)}$$

<u>Comparison of Otto, Diesel and Dual cycle:</u>

(a) For same compression ratio and same heat input

$(\eta_{th})_{Otto} > (\eta_{th})_{Dual} > (\eta_{th})_{Diesel}$

(b) For constant maximum pressure and same heat input

$(\eta_{th})_{Diesel} > (\eta_{th})_{Dual} > (\eta_{th})_{Otto}$

(c) For same maximum pressure and temperature

$(\eta_{th})_{Diesel} > (\eta_{th})_{Dual} > (\eta_{th})_{Otto}$

(d) For same maximum pressure and output

$(\eta_{th})_{Diesel} > (\eta_{th})_{Otto}$