Internal Combustion Engine 1

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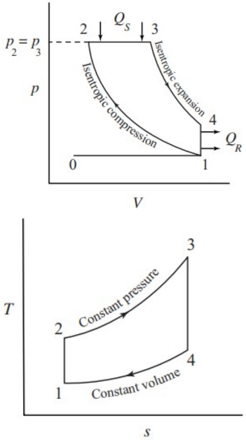
Diesel Cycle

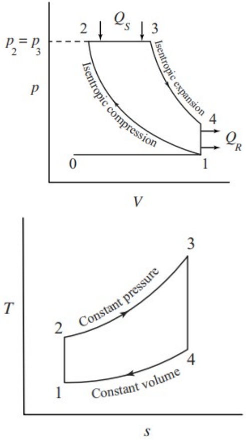
Introduction to Diesel Cycle

- In spark-ignition engines, the compression ratio is constrained by the fuel's self-ignition temperature.
- This constraint is overcome in engines that compress air and fuel separately, mixing them just before combustion.
- In these engines, fuel is injected into hot compressed air, where its temperature exceeds the self-ignition point, leading to auto-ignition.
- These engines, which use heavy liquid fuels, do not need an ignition system.



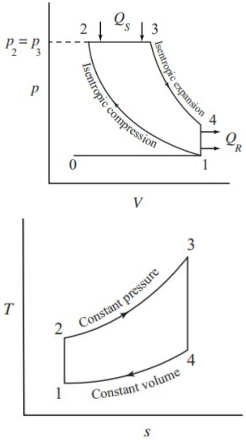
Diesel Cycle Overview

- These engines are known as compression-ignition engines, operating on the ideal Diesel cycle.
- The main difference between the Otto and Diesel cycles lies in how heat is added.
- In the Otto cycle, heat is added at a constant volume.
- In the Diesel cycle, heat addition occurs at a constant pressure.
- This constant-pressure heat addition is why the Diesel cycle is sometimes called the constant-pressure cycle, though this can be confused with the Joule cycle.



Diesel Cycle Analysis

- The Diesel cycle is represented on p-V and T-s diagrams.
- Similar to the Otto cycle, the analysis of the Diesel cycle excludes the suction and exhaust strokes ($0 \to 1$ and $1 \to 0$).
- The volume ratio $\frac{V_1}{V_2}$ is known as the compression ratio, denoted by r.
- The volume ratio $\frac{V_3}{V_2}$ is termed the cut-off ratio, represented by r_c.



Diesel Cycle Efficiency

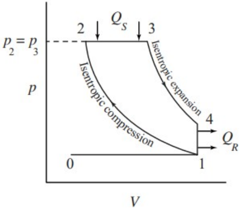
The thermal efficiency of the Diesel cycle is given by:

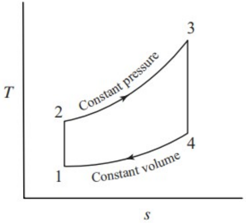
$$\eta_{\text{Diesel}} = \frac{Q_S - Q_R}{Q_S}$$

$$\eta_{\text{Diesel}} = \frac{mC_p(T_3 - T_2) - mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)}$$

$$\eta_{\text{Diesel}} = 1 - \frac{C_v(T_4 - T_1)}{C_p(T_3 - T_2)}$$

$$\eta_{\text{Diesel}} = 1 - \frac{1}{\gamma}\frac{T_4 - T_1}{T_3 - T_2}$$





Efficiency Expression

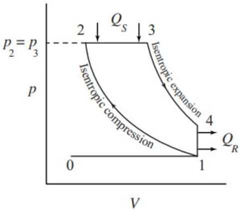
- Considering the process 1→2:

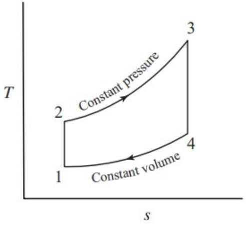
$$T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{\gamma-1} = T_1 r^{(\gamma-1)}$$

- Considering the constant pressure process 2→3:

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

$$T_3 = T_2 r_c = T_1 r^{(\gamma-1)} r_c$$





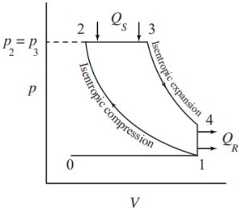
Efficiency Expression - cont.

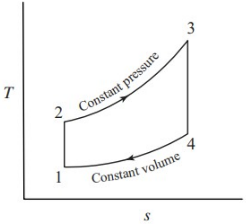
- Considering process 3→4:

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

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

$$T_4 = T_1 r^{(\gamma-1)} r_c \left(\frac{r_c}{r}\right)^{\gamma-1} = T_1 r_c^{\gamma}$$





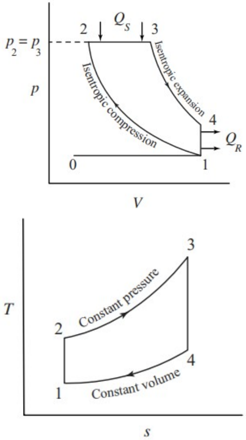
Efficiency Expression - cont.

- Efficiency:

$$\eta_{\text{Diesel}} = 1 - \frac{1}{\gamma}\left[\frac{T_1(r_c^{\gamma} - 1)}{T_1(r^{(\gamma-1)}r_c - r^{(\gamma-1)})}\right]$$

$$\eta_{\text{Diesel}} = 1 - \frac{1}{\gamma}\left[\frac{(r_c^{\gamma} - 1)}{r^{(\gamma-1)}r_c - r^{(\gamma-1)}}\right]$$

$$\eta_{\text{Diesel}} = 1 - \frac{1}{r^{(\gamma-1)}}\left[\frac{(r_c^{\gamma} - 1)}{\gamma(r_c - 1)}\right]$$



Comparison and Practical Implications

- The efficiency of the Diesel cycle differs from the Otto cycle mainly in the bracketed factor.
- This factor is always greater than unity, making the Otto cycle more efficient for a given compression ratio.
- Diesel engines have higher compression ratios (16 to 20) compared to spark-ignition engines (6 to 10).
- Despite the higher efficiency of the Otto cycle, the practical efficiency of diesel engines is higher due to their higher compression ratios.

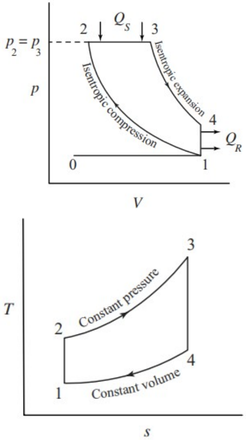
Net Work Output

The net work output for a Diesel cycle is given by:

$$W = p_2(V_3 - V_2) + \frac{p_3V_3 - p_4V_4}{\gamma - 1} - \frac{p_2V_2 - p_1V_1}{\gamma - 1}$$

$$W = p_2V_2(r_c - 1) + \frac{p_3r_cV_2 - p_4rV_2}{\gamma - 1} - \frac{p_2V_2 - p_1rV_2}{\gamma - 1}$$

$$W = V_2\left[\frac{p_2(r_c - 1)(\gamma - 1) + p_3(r_c - \frac{p_4}{p_3}r) - p_2(1 - \frac{p_1}{p_2}r)}{\gamma - 1}\right]$$

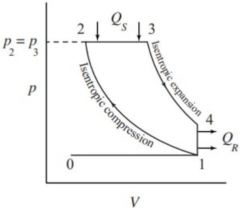


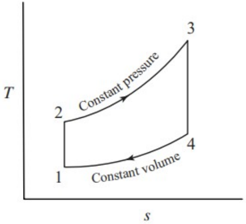
Net Work Output

The net work output for a Diesel cycle is given by:

$$W = p_2 V_2 \left[\frac{(r_c - 1)(\gamma - 1) + (r_c - r_c^{\gamma} r^{(1-\gamma)}) - (1 - r^{(1-\gamma)})}{\gamma - 1} \right]$$

$$W = \frac{p_1 V_1 r^{(\gamma-1)} \left[\gamma (r_c - 1) - r^{(1-\gamma)} (r_c^{\gamma} - 1) \right]}{\gamma - 1}$$





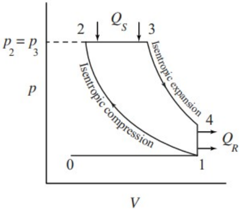
Mean Effective Pressure

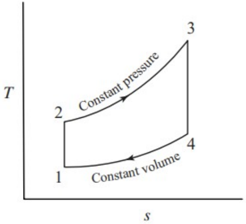
The mean effective pressure is given by:

$$MEP = \frac{W}{\text{Swept Volume}}$$

$$MEP = \frac{p_1 V_1 \left[r^{(\gamma-1)}\gamma(r_c - 1) - (r_c^{\gamma} - 1) \right]}{(\gamma - 1) V_1 \left(\frac{r-1}{r} \right)}$$

$$MEP = \frac{p_1 \left[r^{\gamma}\gamma(r_c - 1) - r(r_c^{\gamma} - 1) \right]}{(\gamma - 1)(r - 1)}$$

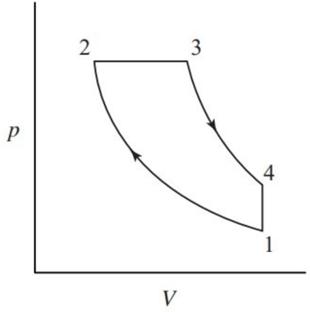




Example 1

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 $\gamma = 1.4$.

$$\begin{aligned}
r &= \frac{V_1}{V_2} = 20 \\
V_1 &= 20V_2 \\
V_s &= 20V_2 - V_2 = 19V_2 \\
V_3 &= 0.05V_s + V_2 \\
&= 0.05 \times 19V_2 + V_2 \\
&= 1.95V_2
\end{aligned}$$



Example 1 - cont.

$$
\begin{aligned}
r_c &= \frac{V_3}{V_2} = \frac{1.95V_2}{V_2} = 1.95 \\
\eta &= 1 - \frac{1}{r^{\gamma-1}} \; \frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)} \\
&= 1 - \frac{1}{20^{0.4}} \times \left[\frac{1.95^{1.4} - 1}{1.4 \times (1.95 - 1)}\right] = 0.649 = \mathbf{64.9\%} \qquad \underleftarrow{\mathbf{Ans}}
\end{aligned}
$$

Example 2

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.

$$
\begin{aligned}
V_s &= \frac{\pi}{4}\ d^2\ L = \frac{\pi}{4} \times 25^2 \times 37.5 \\
&= 18407.8 \text{ cc} \\
r &= 1 + \frac{V_s}{V_c} = 1 + \frac{18407.8}{1500} = 13.27 \\
\eta &= 1 - \frac{1}{r^{\gamma-1}}\ \frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)} \\
r_c &= \frac{V_3}{V_2}
\end{aligned}
$$

Example 2 - cont.

$$\begin{aligned}
\textit{Cut-off volume} &= V_3 - V_2 = 0.05V_s = 0.05 \times 12.27V_c \\
V_2 &= V_c \\
V_3 &= 1.6135V_c \\
r_c &= \frac{V_3}{V_2} = 1.6135 \\
\eta &= 1 - \frac{1}{13.27^{0.4}} \times \frac{1.6135^{1.4} - 1}{1.4 \times (1.6135 - 1)} \\
&= 0.6052 = \mathbf{60.52\%} \qquad \xLeftarrow{\textbf{Ans}}
\end{aligned}$$

Example 3

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.

Example 3 - cont.

Consider the process 1 – 2

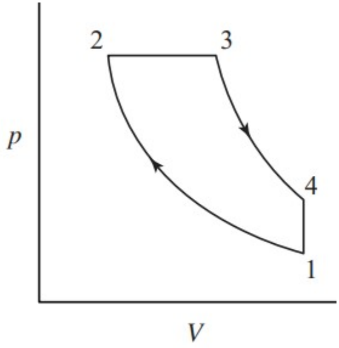
$$\frac{V_1}{V_2} = r$$

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

$$= \left(\frac{35}{1}\right)^{\frac{1}{1.4}} = 12.674$$

$$r_c = \frac{V_3}{V_2} = \frac{V_3}{V_1} \times \frac{V_1}{V_2}$$

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



Example 3 - cont.

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

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

Consider the process $2 - 3$

$$T_3 = T_2 \frac{V_3}{V_2} = 801.7 \times \frac{V_3}{V_2} = 801.7 \times 2.535 = 2032.3 \text{ K}$$

Example 3 - cont.

Consider the process 3 – 4

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{\gamma-1} = 2032.3 \times \left(\frac{1}{5}\right)^{0.4} = 1067.6 \text{ K}$$

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

$$= \mathbf{1235.5 \ kJ/kg} \qquad \stackrel{\text{Ans}}{\Longleftarrow}$$

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

$$= \mathbf{557.5 \ kJ/kg} \qquad \stackrel{\text{Ans}}{\Longleftarrow}$$

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

$$= \frac{1235.5 - 557.5}{1235.5} = 0.549 = \mathbf{54.9\%} \qquad \stackrel{\text{Ans}}{\Longleftarrow}$$

End of Lecture 12

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