The Internal combustion engine (Otto Cycle)

The Otto cycle is a set of processes used by spark ignition internal combustion engines (2-stroke or 4-stroke cycles). These engines

1. Ingest a mixture of fuel and air,
2. Compress it,
3. Cause it to react, thus effectively adding heat through converting chemical energy into thermal energy,
4. Expand the combustion products, and then
5. Eject the combustion products and replace them with a new charge of fuel and air. The different processes are shown in Figure 1.

1. Intake stroke, gasoline vapor and air drawn into engine (5 → 1).
2. Compression stroke, p , T increase (1 → 2).
3. Combustion (spark), short time, essentially constant volume (2 → 3). Model: heat absorbed from a series of reservoirs at temperatures $T_2$ to $T_3$.
5. Valve exhaust: valve opens, gas escapes.
6. (4 → 1) Model: rejection of heat to series of reservoirs at temperatures $T_4$ to $T_1$.
7. Exhaust stroke, piston pushes remaining combustion products out of chamber (1 → 5).

We model the processes as all acting on a fixed mass of air contained in a piston-cylinder arrangement, as shown in Figure 3.

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**Figure 1:** The ideal Otto cycle
The actual cycle does not have the sharp transitions between the different processes that the ideal cycle has, and might be as sketched in Figure 2.

Efficiency of an ideal Otto cycle

The starting point is the general expression for the thermal efficiency of a cycle:

\[ \eta = \frac{\text{work}}{\text{heat input}} = \frac{Q_H + Q_L}{Q_H} = 1 + \frac{Q_L}{Q_H}. \]

The convention, as previously, is that heat exchange is positive if heat is flowing into the system or engine, so \( Q_L \) is negative. The heat absorbed occurs during combustion when the spark occurs, roughly at constant volume. The heat absorbed can be related to the temperature change from state 2 to state 3 as:

\[ Q_H = Q_{23} = \Delta U_{23} \quad (W_{23} = 0) \]

\[ = \int_{T_2}^{T_3} C_v dT = C_v (T_3 - T_2). \]
The heat rejected is given by (for a perfect gas with constant specific heats)
\[ Q_L = Q_{41} = \Delta U_{41} = C_v(T_1 - T_4). \]

Substituting the expressions for the heat absorbed and rejected in the expression for thermal efficiency yields
\[ \eta = 1 - \frac{T_4 - T_1}{T_3 - T_2}. \]

We can simplify the above expression using the fact that the processes from 1 to 2 and from 3 to 4 are isentropic:
\[ T_4 V_1^{\gamma - 1} = T_3 V_2^{\gamma - 1}, \quad T_1 V_1^{\gamma - 1} = T_2 V_2^{\gamma - 1} \]
\[ (T_4 - T_1) V_1^{\gamma - 1} = (T_3 - T_2) V_2^{\gamma - 1} \]
\[ \frac{T_4 - T_1}{T_3 - T_2} = \left( \frac{V_2}{V_1} \right)^{\gamma - 1}. \]

The quantity \( V_1/V_2 = r \) is called the compression ratio. In terms of compression ratio, the efficiency of an ideal Otto cycle is:
\[ \eta_{Otto} = 1 - \frac{1}{(V_1/V_2)^{\gamma - 1}} = 1 - \frac{1}{r^{\gamma - 1}}. \]

**Figure 4**: Ideal Otto cycle thermal efficiency

The ideal Otto cycle efficiency is shown as a function of the compression ratio in Figure 4. As the compression ratio, \( r \), increases, \( \eta_{Otto} \) increases, but so does \( T_2 \). If \( T_2 \) is too high, the mixture will ignite without a spark (at the wrong location in the cycle).
Diesel Cycle

The Diesel cycle is a compression ignition (rather than spark ignition) engine. Fuel is sprayed into the cylinder at \( P_2 \) (high pressure) when the compression is complete, and there is ignition without a spark. An idealized Diesel engine cycle is shown in Figure 1.

**Figure 1:** The ideal Diesel cycle

The Diesel cycle is an ideal air standard cycle which consists of four processes:

1. 1 to 2: Isentropic compression
2. 2 to 3: Reversible constant pressure heating
3. 3 to 4: Isentropic expansion
4. 4 to 1: Reversible constant volume cooling

**Maximum thermal efficiency**

The maximum thermal efficiency of a Diesel cycle is dependent on the compression ratio and the cut-off ratio. It has the following formula under cold air standard analysis:

\[
\eta_{th} = 1 - \frac{1}{r^{\gamma-1}} \left( \frac{\alpha^\gamma - 1}{\gamma(\alpha - 1)} \right)
\]

where

- \( \eta_{th} \) is thermal efficiency
- \( \alpha \) is the cut-off ratio \( V_3/V_2 \) (ratio between the end and start volume for the combustion phase)
- \( r \) is the compression ratio \( V_1/V_2 \)
- \( \gamma \) is ratio of specific heats \( (C_p/C_v) \)

The cut-off ratio can be expressed in terms of temperature as shown below:

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

\[
T_2 = T_1 r^{\gamma-1}
\]

\[
\frac{V_3}{V_2} = \frac{T_3}{T_2}
\]
The Diesel cycle is a combustion process of a reciprocating internal combustion engine. In it, fuel is ignited by heat generated by compressing air in the combustion chamber, into which fuel is injected. This is in contrast to igniting it with a spark plug as in the Otto cycle (four-stroke/petrol) engine. Diesel engines (heat engines using the Diesel cycle) are used in automobiles, power generation, Diesel-electric locomotives, and submarines.

The Dual Cycle

Process 2-3: Constant volume heat addition.
Process 3-4: Constant pressure heat addition.
Process 4-5: Reversible adiabatic expansion.
Process 5-1: Constant volume heat reject
The cycle is the equivalent air cycle for reciprocating high speed compression ignition engines. The P-V and T-s diagrams are shown in Figs. 11 and 12. In the cycle, compression and expansion processes are isentropic; heat addition is partly at constant volume and partly at constant pressure while heat rejection is at constant volume as in the case of the Otto and Diesel cycles.

The heat supplied, $Q_s$ per unit mass of charge is given by

$$Q_s = c_v(T_3 - T_2) + c_p(T_3' - T_2)$$

whereas the heat rejected, $Q_r$ per unit mass of charge is given by

$$Q_r = c_v(T_4 - T_1)$$

and the thermal efficiency is given by

$$\eta_{th} = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2) + c_p(T_3' - T_2)}$$
Comparison of Otto, Diesel and Dual Cycles:

The important variable factors which are used as the basis for comparison of the cycles are compression ratio, peak pressure, heat addition, heat rejection and the net work. In order to compare the performance of the Otto, Diesel and Dual combustion cycles, some of the variable factors must be fixed. In this section, a comparison of these three cycles is made for the same compression ratio, same heat addition, constant maximum pressure and temperature, same heat rejection and net work output. This analysis will show which cycle is more efficient for a given set of operating conditions.

Case 1: Same Compression Ratio and Heat Addition:

The Otto cycle 1-2-3-4-1, the Diesel cycle 1-2-3′-4′-1 and the Dual cycle 1-2-2″-3″-4″-1 are shown in p-V and T-θ diagram in Fig. (a) and (b) respectively for the same compression ratio and heat input.
From the $T$-$s$ diagram, it can be seen that Area $5-2-3-6 = Area$ $5-2-3'-6' = Area$ $5-2-2''-3''-6''$ as this area represents the heat input which is the same for all cycles. All the cycles start from the same initial state point 1 and the air is compressed from state 1 to 2 as the compression ratio is same. It is seen from the $T$-$s$ diagram for the same heat input, the heat rejection in Otto cycle (area $5-1-4-6$) is minimum and heat rejection in Diesel cycle ($5-1-4'-6'$) is maximum. Consequently, Otto cycle has the highest work output and efficiency. Diesel cycle has the least efficiency and Dual cycle having the efficiency between the two.

One more observation can be made i.e., Otto cycle allows the working medium to expand more whereas Diesel cycle is least in this respect. The reason is heat is added before expansion in the case of Otto cycle and the last portion of heat supplied to the fluid has a relatively short expansion in case of the Diesel cycle.

Case 2: Same Compression Ratio and Heat Rejection:
Efficiency of Otto cycle is given by

\[ \eta_{\text{otto}} = 1 - \frac{Q_R}{Q_S} \]

Where, \(Q_s\) is the heat supplied in the Otto cycle and is equal to the area under the curve 2-3 on the T-s diagram [Fig. (b)]. The efficiency of the Diesel cycle is given by,
Where $Q'$ is heat supplied in the Diesel cycle and is equal to the area under the curve 2-3' on the T-s diagram [Fig. (b)]. From the T-s diagram in Fig., it is clear that $Q_s > Q'$ i.e., heat supplied in the Otto cycle is more than that of the Diesel cycle. Hence, it is evident that, the efficiency of the Otto cycle is greater than the efficiency of the Diesel cycle for a given compression ratio and heat rejection.

**Case 3: Same Peak Pressure, Peak Temperature and Heat Rejection:**

Figures (a) and (b) show the Otto cycle 1-2-3-4 and Diesel cycle 1-2'-3'-4 on p-V and T-s coordinates, where the peak pressure and temperature and the amount of heat rejected are the same.

The efficiency of the Otto cycle,

$$ \eta_{otto} = 1 - \frac{Q_R}{Q_S} $$

Where, $Q_s$ in the area under the curve 2-3 in Fig. (b). The efficiency of the Diesel cycle, 1-2-3-4 is,

$$ \eta_{Diesel} = 1 - \frac{Q_R}{Q_s'} $$
It is evident from Fig. that Qs > Q’s. Therefore, the Diesel cycle efficiency is greater than the Otto cycle efficiency when both engines are built to withstand the same thermal and mechanical stresses.

Case 4: Same Maximum Pressure and Heat Input:
For same maximum pressure and heat input, the Otto cycle (1-2-3-4-1) and Diesel cycle (1-2'-3'-4'-1) are shown on p-V and T-s diagrams in Fig. (a) and (b) respectively. It is evident from the figure that the heat rejection for Otto cycle (area 1-5-6-4 on T-s diagram) is more than the heat rejected in Diesel cycle (1-5-6'-4'). Hence Diesel cycle is more efficient than Otto cycle for the condition of same maximum pressure and heat input. One can make a note that with these conditions, the Diesel cycle has higher compression ratio than that of Otto cycle. One should also note that the cycle which is having higher efficiency allows maximum expansion. The Dual cycle efficiency will be between these two.

**Case 5: Same Maximum Pressure and Work Output:**

The efficiency, $\eta$ can be written as

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{\text{Work done}}{\text{Work done} + \text{Heat rejected}}$$

Refer to T-s diagram in Fig. (b). For same work output the area 1-2-3-4 (work output of Otto cycle) and area 1-2'-3'-4' (work output of Diesel cycle) are same. To achieve this, the entropy at 3 should be greater than entropy at 3'. It is clear that the heat rejection for Otto cycle is more than that of diesel cycle. Hence, for these conditions, the Diesel cycle is more efficient than the Otto cycle. The efficiency of Dual cycle lies between the two cycles.
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2008B4A4491H