Centre of Excellence in Renewable Energy Education and Research,
New Campus, University of Lucknow,
Lucknow
B Voc. Renewable Energy Technology
Semester II First Year
Module RET-203: Power Plant Engineering

Unit-2 (Air Standard cycle and Diesel Electric Power Plant)

Contents:

Internal Combustion Engine and External Combustion Engine: Otto Cycle, Diesel Cycle, Dual Cycle, Efficiency and Indicator Diagram.

Diesel Electric Power Plant: Working Principle, Layout, Performance and Thermal Efficiency, Combined Cycle Power Plant, Layout, Efficiency.

Internal Combustion Engine and External Combustion Engine

In an external combustion engine, the fuel isn't burned inside the engine. With an internal combustion engine, the combustion chamber lies right in the middle of the engine.

An **Internal combustion engines** rely on the explosive power of the fuel within the engine to produce work. In internal combustion engines, the explosion forcefully pushes pistons or expels hot high-pressure gas out of the engine at great speeds. Both moving pistons and ejected high-speed gas have the ability to do work. In external combustion engines, combustion heats a fluid which, in turn, does all the work.

Example: Atkinson, Brayton/Joule, Diesel, Otto, Gas Generator etc.

An **external combustion engine** uses a working fluid, either a liquid or a gas or both, that is heated by a fuel burned outside the engine. The external combustion chamber is filled with a fuel and air mixture that is ignited to produce a large amount of heat. This heat is then used to heat the internal working fluid either through the engine wall or a heat exchanger. The fluid expands when heated, acting on the mechanism of the engine, thus producing motion and usable work.

Example: Bell Coleman, Brayton/Joule, Carnot, Stirling, Eriction etc.

Otto Cycle (Petrol Engine)

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 a) ingest a mixture of fuel and air, b) compress it, c) cause it to react, thus effectively adding heat through converting chemical energy into thermal energy, d) expand the combustion products, and then e) 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 ($5 \rightarrow 1$).
2. Compression stroke, P & T increase ($1 \rightarrow 2$).
3. Combustion (spark), short time, essentially constant volume ($2 \rightarrow 3$). Model: heat absorbed from a series of reservoirs at temperatures T_2 to T_3 .
4. Power stroke: expansion ($3 \rightarrow 4$).
5. Valve exhaust: valve opens, gas escapes.
6. ($4 \rightarrow 1$) 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 ($1 \rightarrow 5$).

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

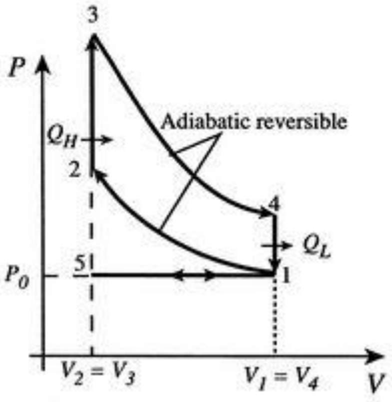


Figure 1: The ideal Otto cycle

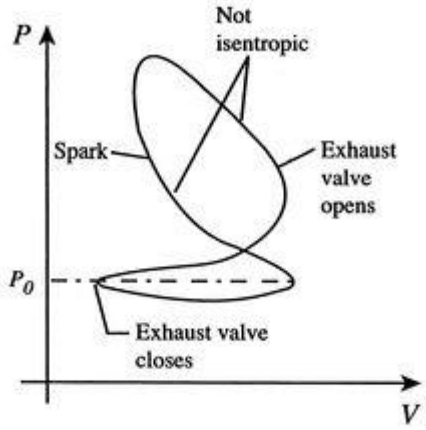


Figure 2: Sketch of an actual Otto cycle

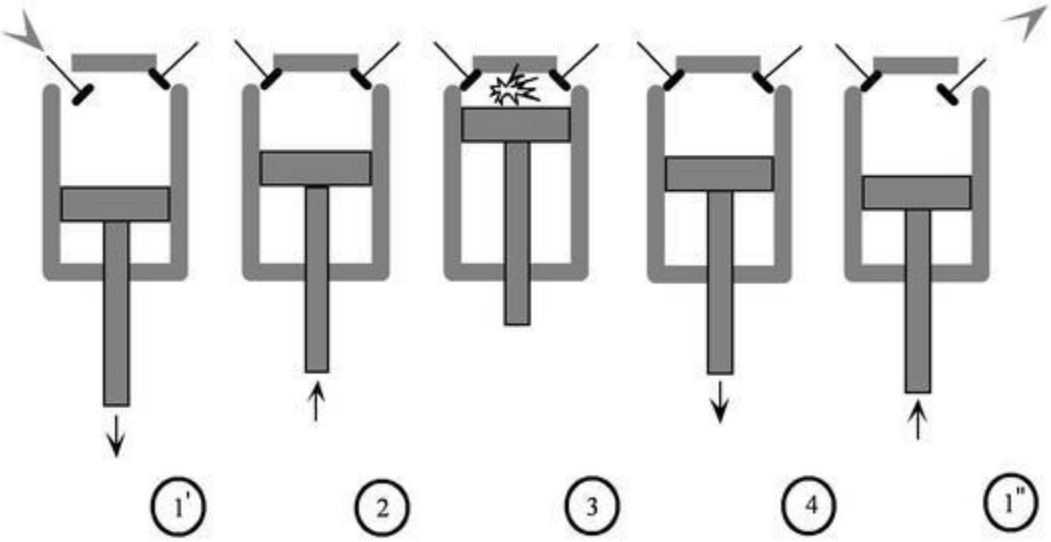


Figure 3: Piston and valves in a four-stroke internal combustion engine

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:

$$\begin{aligned} Q_H &= Q_{23} = \Delta U_{23} \qquad (W_{23} = 0) \\ &= \int_{T_2}^{T_3} C_v dT = C_v(T_3 - T_2). \end{aligned}$$

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:

$$T_4 V_1^{\gamma-1} = T_3 V_2^{\gamma-1}, \qquad T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

$$(T_4 - T_1)V_1^{\gamma-1} = (T_3 - T_2)V_2^{\gamma-1}$$

$$\frac{T_4 - T_1}{T_3 - T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}.$$

The quantity $\frac{V_1}{V_2} = r$ is called the compression ratio. In terms of compression ratio, the efficiency of an ideal Otto cycle is:

$$\eta_{\text{Otto}} = 1 - \frac{1}{(V_1/V_2)^{\gamma-1}} = 1 - \frac{1}{r^{\gamma-1}}.$$

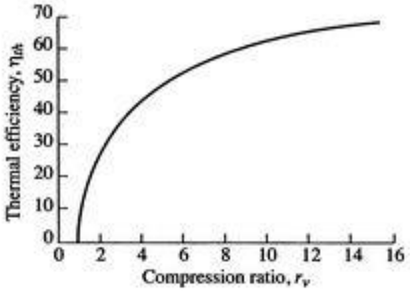


Figure 4: Ideal Otto cycle thermal efficiency

The ideal Otto cycle efficiency is shown as a function of the compression ratio in **Figure 4**. As the compression ratio, r, increases, η_{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

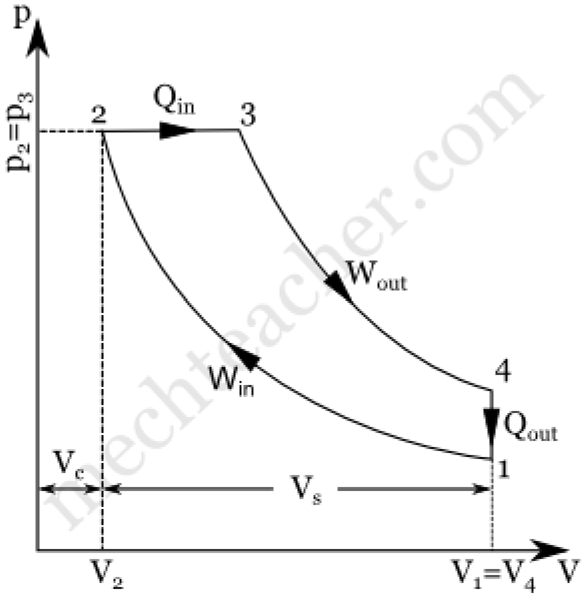
Diesel cycle is a gas power cycle invented by Rudolph Diesel in the year 1897. It is widely used in diesel engines.

Diesel cycle is similar to Otto cycle except in the fact that it has one constant pressure process instead of a constant volume process (in Otto cycle).

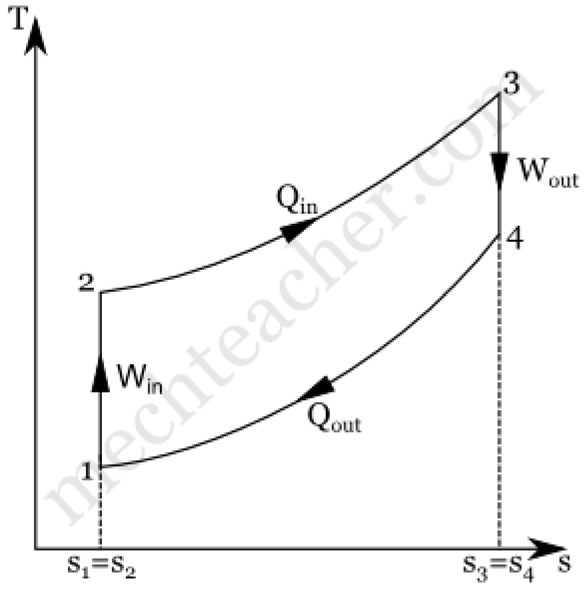
Diesel cycle can be understood well if you refer its P-V and T-s diagrams.

P-V and T-s Diagrams of Diesel Cycle:

P-V Diagram



T-s Diagram



Processes in Diesel Cycle:

Diesel cycle has four processes. They are:

1. Process 1-2: Isentropic (Reversible adiabatic) Compression
2. Process 2-3: Constant Pressure (Isobaric) Heat Addition
3. Process 3-4: Isentropic Expansion
4. Process 4-1: Constant Volume (Isochoric) Heat Rejection

Process 1-2: Isentropic Compression

In this process, the piston moves from Bottom Dead Centre (BDC) to Top Dead Centre (TDC) position. Air is compressed isentropically inside the cylinder. Pressure of air increases from P_1 to P_2, temperature increases from T_1 to T_2, and volume decreases from V_1 to V_2. Entropy remains constant (i.e., $s_1 = s_2$). Work is done on the system in this process (denoted by W_{in} in the diagrams above).

Process 2-3: Constant Pressure Heat Addition

In this process, heat is added at constant pressure from an external heat source. Volume increases from V_2 to V_3, temperature increases from T_2 to T_3 and entropy increases from s_2 to s_3.

Heat added in process 2-3 is given by

$Q_{in} = mC_p(T_3 - T_2)$ kJ ………… (i)

Where,

m = Mass of air in kg

C_p = Specific heat at constant pressure in kJ/kg-K

T_2 = Temperature at point 2 in K

T_3 = Temperature at point 3 in K

Process 3-4: Isentropic Expansion

Here the compressed and heated air is expanded isentropically inside the cylinder. The piston is forced from TDC to BDC in the cylinder. Pressure of air decreases from p_3 to p_4, temperature decreases from T_3 to T_4, and volume increases from V_3 to V_4. Entropy remains constant (i.e., $s_3 = s_4$). Work is done by the system in this process (denoted by W_{out} in the P-V and T-s diagrams above).

Process 4-1: Constant Volume Heat Rejection

In this process, heat is rejected at constant volume ($V_4 = V_1$). Pressure decreases from P_4 to P_1, temperature decreases from T_4 to T_1 and entropy decreases from s_4 to s_1.

Heat rejected in process 4-1 is given by

$Q_{out} = mC_v(T_4 - T_1)$ kJ ………… (ii)

Where,

m = Mass of air in kg

C_v = Specific heat at constant volume in kJ/kg-K

T_2 = Temperature at point 2 in K

T_3 = Temperature at point 3 in K

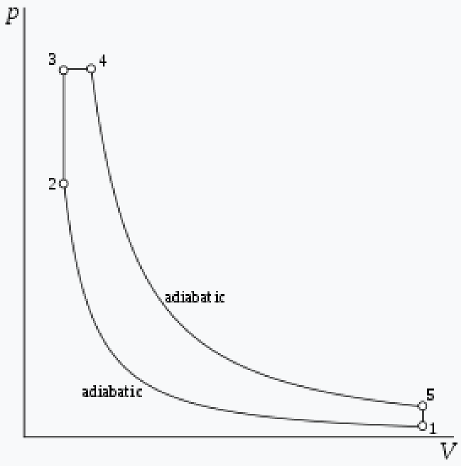
Air-standard Efficiency of Diesel Cycle:

Air-standard efficiency (or thermal efficiency) of diesel cycle is given by:

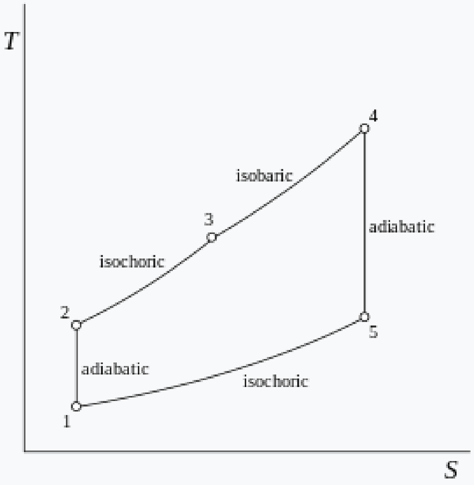
$$\begin{aligned}\eta_{\text{Diesel}} &= 1 + \frac{Q_L}{Q_H} = 1 + \frac{C_v(T_1 - T_4)}{C_p(T_3 - T_2)} \\ &= 1 - \frac{T_1}{\gamma T_2}\frac{(T_4/T_1 - 1)}{(T_3/T_2 - 1)}.\end{aligned}$$

Dual Cycle

The dual combustion cycle (also known as the mixed cycle) is a thermal cycle that is a combination of the Otto cycle and the Diesel cycle, first introduced by Russian-German engineer Gustav Trinkler, who never claimed to have developed the cycle though. Heat is added partly at constant volume (isochoric) and partly at constant pressure (isobaric), the significance of which is that more time is available for the fuel to completely combust. Because of lagging characteristics of fuel this cycle is invariably used for Diesel and hot spot ignition engines. It consists of two adiabatic and two constant volume and one constant pressure processes.



P-V diagram of Dual cycle



T-s diagram of Dual cycle

The dual cycle consists of following operations:

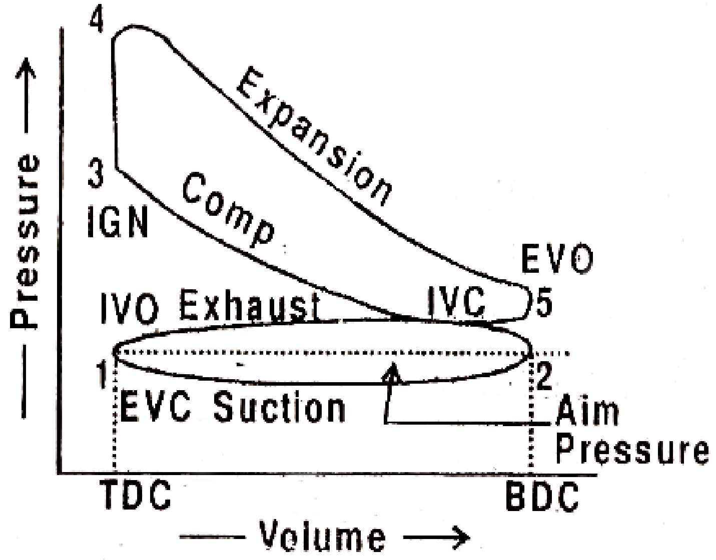
- Process 1-2: Isentropic compression
- Process 2-3: Addition of heat at constant volume.
- Process 3-4: Addition of heat at constant pressure.
- Process 4-5: Isentropic expansion.
- Process 5-1: Rejection of heat at constant volume.

Indicator Diagram

Indicator diagram is one of the most important ratings for assessing the internal combustion engine. Indicator diagrams indicate, simultaneously, the pressures and the relative position of the piston for a particular engine cylinder. They are taken for every state, both in loaded and equilibrium condition. Diagram is used to: - calculate indicated power of the engine, - determine peak pressures and compression pressures, - evaluate the process of combustion inside the engine, - evaluate scavenging and exhausting conditions. An indicator diagram shall be determined by a set of components: - indicator with combustion pressure sensor and load sensor, - crankshaft position sensor, - recorder.

Indicator diagram shows the difference between the theoretical circulation and circulation actual realized in the test engine. These differences may result from: - the engine working medium is exchanged after each cycle, - by chemical reaction decompressed medium has different physical properties than the compressed medium, - due to leakage cylinder piston amount of medium is changed, - heat is not supplied from outside, but obtained either the combustion of the fuel in the cylinder, - the course of the heat supply is not consistent with the assumptions p = constants and V = constants, - occurs incomplete combustion, - compression and decompression isn't isotropic (at the beginning heat is supplied from warm cylinder surface to medium, next heat is dissipate from exhaust gasses to cylinder surface and cylinder head.

In practice, the engine it is known that operation cycle in the same cylinder can vary between each other. This phenomenon is called the uniqueness of consecutive cycles. The essential causes are: - unequal filling of the cylinder fresh charge, - unequal combustion process.



Indicator Diagram For A Four Stroke Cycle Petrol Engine.

Diesel Electric Power Plant