

THERMAL ENGINEERING I

**LECTURE NOTES ON
THERMAL ENGINEERING -I**

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THERMAL ENGINEERING I

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THERMAL ENGINEERING I

THERMODYNAMIC CONCEPT AND TERMINOLOGY

Thermodynamic Concepts

Thermal engineering

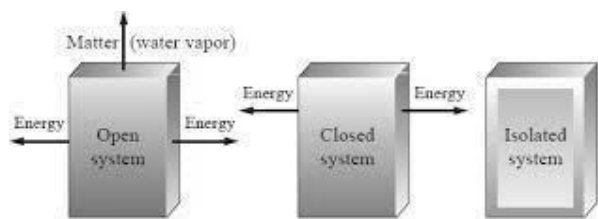
- Thermal engineering is the study of energy transfer and its effects on various cooling and heating applications.
- It includes the science of thermodynamics, fluid mechanics, and heat and mass transfer.
- It has applications in- HVAC (heating, ventilation, and air conditioning), cooling of computer chips, boiler design, combustion engines, refrigeration, heat exchangers and thermal power plants.

Thermodynamics

- Thermodynamics is the science of energy interactions like work, heat and mass transfer between a system and the surroundings and its effect on the properties of the system.
- The principles of energy conversion in thermodynamics are governed by thermodynamic laws.
- The applications of thermodynamic laws are found in IC engines, gas turbines, air conditioning, refrigeration, steam and nuclear power plants.

Thermodynamic system

- A thermodynamic system is the quantity of matter or a region in space upon which attention is concentrated in the analysis of a problem.
- Everything external to the system is called the surrounding.
- Boundary is an enclosure that separates the system from its surrounding. It can either be fixed or moving.
- Together system and surrounding comprise a universe.
- There are three classes of systems-
 - Open system
 - Closed system
 - Isolated system



→ Open System

- It's a system where both mass and energy cross the boundary of the system.
- All engineering devices are generally open systems, e.g., air compressors

→ Closed System

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- It's a system of fixed mass. Hence no mass transfer across the boundary takes place.
- Here energy transfer takes place across the system boundary.

→ Isolated System

- It's a system where there's no interaction of mass and energy between the system and the surroundings.
- It's a system of fixed mass and energy.

Macroscopic and Microscopic Views

→ Thermodynamic studies are undertaken by the following two different points of view:

- Macroscopic view
- Microscopic view

→ In this approach, a certain quantity of matter is considered without taking into account the events occurring at molecular level.

→ This approach to thermodynamics which is concerned with gross or overall behaviour is known as classical thermodynamics.

→ The analysis of macroscopic system requires simple mathematical formulae.

→ The values of the properties of the system are their average values. For example, the pressure of the gas in a closed container is the average value of the pressure exerted by millions of individual molecules. Or, the temperature of this gas is the average value of translational kinetic energies of millions of individual molecules.

→ Here, only few properties are needed to describe a system.

Microscopic View

In this approach, a system made up of very large number of discrete particles, known as molecules, is considered.

This approach to thermodynamics which is concerned directly with the structure of the matter is known as statistical thermodynamics.

The analysis of microscopic system requires advanced statistical and mathematical methods.

The properties like velocity, momentum, impulse, kinetic energy cannot be easily measured.

Here, large number of variables is needed to describe a system.

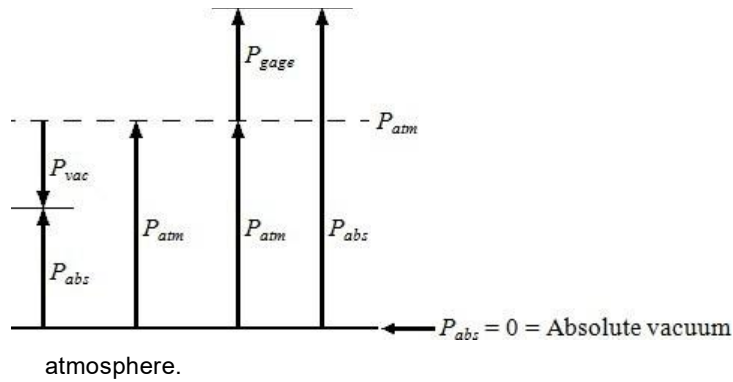
Thermodynamic Properties of a System

Pressure

→ Pressure is defined as the normal force per unit area.

→ It's the difference between the pressure exerted by a fluid of interest and the ambient atmospheric pressure.

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→ The pressure above the atmospheric pressure is termed gauge pressure and it is positive.

→ The pressure below the atmospheric pressure is termed vacuum and it is negative. The vacuum readings are given in mm of Hg or mm of water below

→ The pressure measured above the absolute zero of pressure is termed absolute pressure.

Mathematically,

$$\text{Absolute pressure} = \text{Gauge pressure} + \text{Atmospheric pressure}$$

$$\text{i.e., } p_{abs} = p_{gauge} + p_{atm}$$

$$\text{and, Vacuum pressure} = \text{Atmospheric pressure} - \text{Absolute pressure}$$

$$\text{i.e., } p_{vac} = p_{atm} - p_{abs}$$

Vacuum is defined as the absence of pressure. A perfect vacuum is obtained when absolute pressure is zero, at this instant the molecular momentum is zero.

The atmospheric pressure is measured with the help of barometer.

Unit

The unit of pressure in SI is pascal (Pa) where,

$$1Pa = 1 N/m^2.$$

The other two widely used units are- bar and standard atmospheric pressure, where

$$1bar = 10^5 Pa = 100kPa = 0.1MPa \text{ and,}$$

$$1atm = 101.325kPa = 1.01325bar$$

Low pressures are often expressed in term of mm of water (mmH₂O) or mm of mercury(mmHg).

$$\text{Hence, } 1atm = 760mmHg = 0.76m$$

Also,

$$1MPa = 1 N/mm^2 = 10^6 N/m^2$$

$$1mmHg = 133.3 N/m^2$$

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$$1 \text{ N/m}^2 = 7.5 \times 10^{-3} \text{ mmHg}$$

Specific Volume

→ The specific volume is defined as the volume occupied by a unit mass of a system. It's given by,

$$v = V/m. \text{ Its unit is } m^3/kg.$$

→ It's also the reciprocal of density.

Temperature

→ Temperature is the thermal state of a body that distinguishes a hot body from a cold body. It is proportional to the stored molecular energy of a system.

→ Thermometers are used for measuring ordinary temperatures. For measuring high temperatures, pyrometers are used.

→ The relation between Celsius and Fahrenheit scale is given by, $^{\circ}\text{C} = \frac{^{\circ}\text{F} - 32}{9} \times 5$

→ The relation between Kelvin (absolute scale) and Celsius scale is given by,

$$T(K) = t(^{\circ}\text{C}) + 273.15$$

Thermodynamic Equilibrium

→ A system is said to exist in a state of thermodynamic equilibrium when no change in any macroscopic property is registered, if the system is isolated from its surroundings.

→ A system will be in a state of thermodynamic equilibrium, if the conditions for the following three types of equilibrium are satisfied:

- Mechanical equilibrium
- Chemical equilibrium
- Thermal equilibrium
- Mechanical equilibrium

→ A system is said to be in a state of mechanical equilibrium when there's an absence of any unbalanced force within the system or between the system and the surroundings.

→ If an unbalanced force exists, either the system or both the system and the surroundings will undergo a change of state till mechanical equilibrium is restored.

Chemical equilibrium: A system is said to exist in a state of thermodynamic equilibrium if there's no chemical reaction or transfer of matter, such as diffusion, from one part to another part of the system.

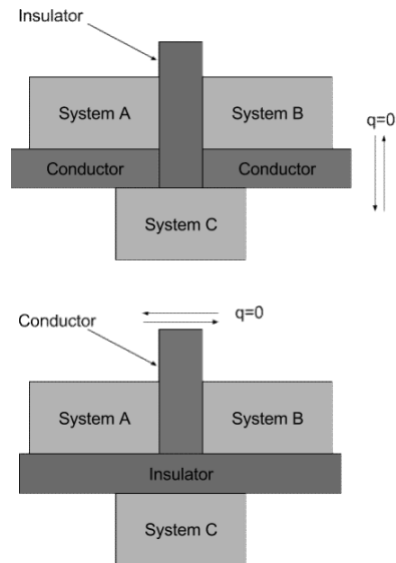
Thermal equilibrium: When a system existing in mechanical and chemical equilibrium is separated by a diathermic barrier and no spontaneous change in any property occurs then the system is said to exist in a state of thermal equilibrium.

When the conditions for any one of the three types of equilibrium are not satisfied, a system is said to be in a non-equilibrium state.

Zeroth Law of Thermodynamics

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When a body A is in thermal equilibrium with a body B, and also separately with a body C, then B and C will be in thermal equilibrium with each other.



Intensive and Extensive Properties

→ The property of a system is certain characteristics of the system by which its physical condition may be described. The property is of two types:

→ Intensive Properties

→ The properties that are independent of the mass of the system are intensive properties.

Example- Temperature, pressure, specific volume etc.

Extensive Properties

These properties depend on the mass of the system i.e., if mass is increased, the value of the extensive property also increase.

Example- Volume, energy, etc.

Specific extensive properties i.e., extensive properties per unit mass, are intensive properties, e.g., specific volume, specific energy, etc.

State and Process

→ State is the physical condition of a system at an instant of time where all its properties have definite values. It's also described as the unique condition of a system.

→ The properties are the coordinates to describe the state of a system and are identical for identical states. Hence, all properties are state or point functions.

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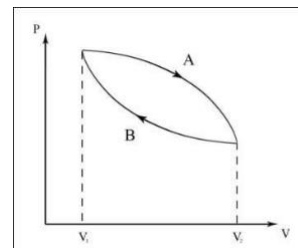
- The variable is a property, if and only if, it has a single at each equilibrium state, or the change in its value between any two prescribed equilibrium states is single-valued.
- Any operation in which one or more of the properties of a system changes is called a change of state.
- The succession of states passed through by a system during a state change is called a path.

Process

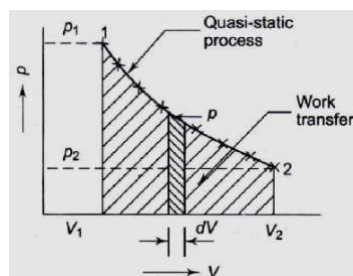
- A system undergoing a change of state or an energy transfer at a steady state is called a process.
- A process in which a fixed mass within a defined boundary undergoes a change of state is called a non-flow process. Closed systems undergo a non-flow process.
- A process in which there's a constant transfer of mass across the system boundary is called a flow process. Open systems undergo a flow process.
- A reversible process is one where both the system and the surroundings return to their original initial conditions. It's also called a quasi-static process.
- In an irreversible process the system and the surroundings don't return to their initial conditions.

Cycle

- Any process or a series of processes whose end states are identical is termed a cycle.
- It is also defined as the series of state changes where the final state and the initial state are identical.



Quasi-static process



- It's a process where a system passes through a succession of equilibrium states.
- The term quasi means almost.
- It's a reversible process and infinite slowness is the characteristic feature of this process.

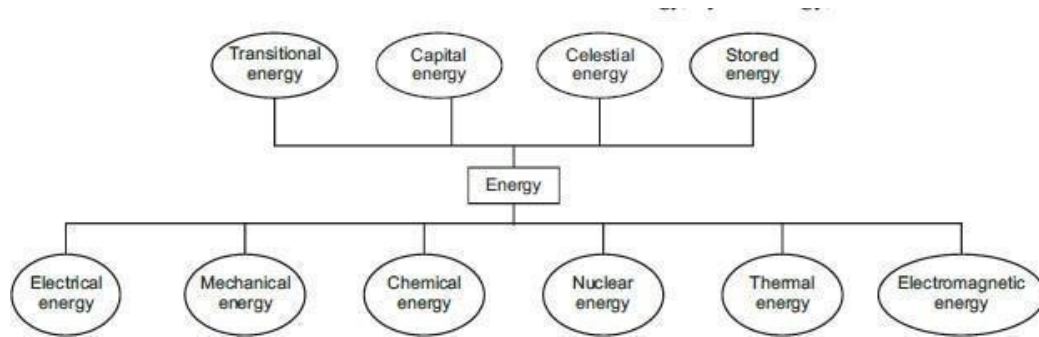
Conceptual Explanation of Energy and its Sources

Energy

Energy is defined as the capacity to do work. It is a scalar quantity. It is measured in kJ in SI units, and kcal in MKS units.

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Sources of Energy



Work and Heat

Work

- Work is defined as the energy transfer associated with force acting through a distance.
- In thermodynamics point of view, work interaction occurs as the sole effect on things external to the system can be reduced to the raising of weight.
- When a work is done by a system, it is taken as positive and when work is done on a system, it is taken as negative.
- In SI, work is expressed as **J (Joule=1Nm)**.
- The rate at which work is done by, or upon a system is known as power. The unit of power is **W (watt) or J/s**.

$$1 \text{ hp} = 0.746 \text{ kW}$$

Heat

- Heat is a form of energy that is transferred across a boundary by virtue of temperature difference.
- Heat, like work, is a form of energy in transit and a boundary phenomenon.
- The heat flow into a system is taken as positive and that out of the system is taken as negative.
- The unit of heat is **Joule (J)** in SI units.
- The energy transfer by virtue of temperature difference is called *heat transfer* and is expressed in **W or kW**.

Specific Heat and Heat Capacity

- **Specific heat (c)** is defined as the heat energy required to change the temperature of the unit mass of a substance by one degree. Mathematically,

$$c = \frac{1}{m} \left(\frac{\delta Q}{dT} \right) = \frac{\delta q}{dT}$$

- It is measured in **kJ/kgK or kJ/kg°C**
- The product of mass and specific heat is defined as **heat capacity (C)** of the system. It is measured in **kJ/K or kJ/°C**.

Displacement Work for Various Quasi-Static Processes

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→ Constant pressure process (isobaric/isopiestic process)

$$W_{1-2} = \int_{V_1}^{V_2} p dV = p(V_2 - V_1)$$

→ Constant volume process (isochoric process)

$$W_{1-2} = \int p dV = 0$$

→ Isothermal Process

$$W_{1-2} = p_1 V_1 \ln \left(\frac{V_2}{V_1} \right)$$

→ Reversible adiabatic Process

$$W_{1-2} = \frac{p_1 V_1 - p_2 V_2}{\gamma - 1}$$
$$W_{1-2} = \frac{p_1 V_1}{\gamma - 1} \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} \right]$$

→ Polytropic Process

$$W_{1-2} = \frac{p_1 V_1}{n - 1} \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \right]$$

LAWS OF THERMODYNAMICS

Zeroth Law of Thermodynamics

First law of Thermodynamics

This law may be stated as follows,

- a. **The heat and mechanical work are mutually convertible**, i.e. when a closed system undergoes a thermodynamic cycle,
 - i. The net heat transfer is equal to the net work transfer, or
 - ii. The cyclic integral of heat transfers is equal to the cyclic integral of work transfers.

Mathematically,

$$\Sigma W_{cycle} = \Sigma Q_{cycle}$$

$$\oint dW = \oint dQ$$

- b. **The energy can neither be created nor destroyed**; it can only be transformed from one form to another. This law is also known as the principle of conservation of energy.

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- i. According to this law, a system undergoing a change of state includes both heat and work transfers.
- ii. The net energy stored within the system is known as stored energy or total internal energy E .

Mathematically,

$$Q - W = \Delta E$$

Limitations of First law of Thermodynamics

First law does not impose any restriction on the direction in which the process is feasible. Some common examples are as follows,

- A cup of hot coffee left in a cooler room eventually cools off. The reverse of this process- coffee getting hotter as a result of heat transfer from a cooler room does not take place.
- Consider heating of a room by passage of electric current through an electric resistor. Transferring of heat from room will not cause electrical energy to be generated through the wire.
- Water flows down hill where by potential energy is converted into K.E. Reverse of this process does not occur in nature.

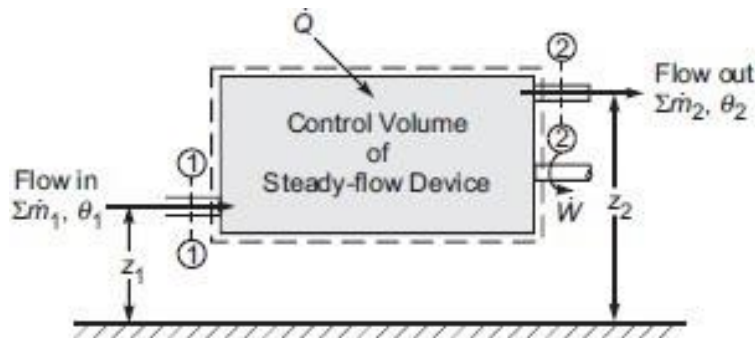
Application of First law of Thermodynamics

Flow Process and Flow Energy

Flow Process constitutes an open system in which the working substance enters and leaves the control surface of a system.

Flow energy or flow work refers to work required to push a certain mass of fluid into and out of the control volume.

Mass balance and Energy Balance in a Simple Steady Flow Process



For a certain steady flow system, the invariant properties are defined below;

A_1, A_2 = cross section of stream, m^2

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\dot{m}_1, \dot{m}_2 = mass flow rate, kg/s

p_1, p_2 = absolute pressure, N/m²

v_1, v_2 = Specific volume, m³/kg

u_1, u_2 = Specific internal energy, J/kg

V_1, V_2 = Velocity, m/s

Z_1, Z_2 = elevation above an arbitrary datum, m

$\frac{\delta Q}{dt}$ = net rate of heat transfer through the control surface, J/s

$\frac{\delta W}{dt}$ = net rate of work transfer through the control surface, J/s

Mass Balance

If there's no accumulation of mass within the control volume therefore by the conservation of mass, the mass flow rate entering is equal to the mass flow rate leaving, or

$$\dot{m}_1 = \dot{m}_2$$
$$\frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2}$$

The above equation is called the **equation of continuity**.

Energy Balance

The work transfer involved in a flow process is: **external work** and **flow work**.

The external work occurring in this system is **shaft work**.

The flow work in the steady flow system is the displacement work done by the fluid of mass dm_1 at inlet 1 and that of mass dm_2 at the exit section 2. Therefore, the total work transfer is given by,

$$W = W_x - p_1 v_1 dm_1 + p_2 v_2 dm_2$$

In the rate form,

$$\frac{\delta W}{dt} = \frac{\delta W_x}{dt} - p_1 v_1 \frac{dm_1}{dt} + p_2 v_2 \frac{dm_2}{dt}$$

Or,

$$\frac{\delta W}{dt} = \frac{\delta W_x}{dt} - \dot{m}_1 p_1 v_1 + \dot{m}_2 p_2 v_2$$



Since there's no accumulation of mass, by the conservation of energy, the total energy rate of all streams entering the CV must equal the total energy rate of all streams leaving the CV, i.e.

$$\dot{m}_1 e_1 + \frac{\delta Q}{dt} = \dot{m}_2 e_2 + \frac{\delta W}{dt}$$

Now,

$$\dot{m}_1 e_1 + \frac{\delta Q}{dt} - \dot{m}_2 e_2 = \frac{\delta W_x}{dt} \quad \dot{m}_1 p_1 v_1 + \dot{m}_2 p_2 v_2$$

or, $\dot{m}_1 e_1 + \dot{m}_1 p_1 v_1 + \frac{\delta Q}{dt} = \dot{m}_2 e_2 + \dot{m}_2 p_2 v_2 + \frac{\delta W_x}{dt}$

The specific energy e is given by,

$$e = e_k + e_p + u$$

$$= \frac{V^2}{2} + gZ + u$$

Therefore,

$$\dot{m}_1 \left(\frac{V_1^2}{2} + gZ_1 + u_1 \right) + \dot{m}_1 p_1 v_1 + \frac{\delta Q}{dt} = \dot{m}_2 \left(\frac{V_2^2}{2} + gZ_2 + u_2 \right) + \dot{m}_2 p_2 v_2 + \frac{\delta W_x}{dt}$$

or, $\dot{m}_1 \left(\frac{V_1^2}{2} + gZ_1 + u_1 + p_1 v_1 \right) + \frac{\delta Q}{dt} = \dot{m}_2 \left(\frac{V_2^2}{2} + gZ_2 + u_2 + p_2 v_2 \right) + \frac{\delta W_x}{dt}$

$$\dot{m}_1 \left(\frac{V_1^2}{2} + gZ_1 + h_1 \right) + \frac{\delta Q}{dt} = \dot{m}_2 \left(\frac{V_2^2}{2} + gZ_2 + h_2 \right) + \frac{\delta W_x}{dt}$$

Where, $h = u + pv$

As, $\dot{m}_1 = \dot{m}_2 = \dot{m} = \frac{dm}{dt}$

So,

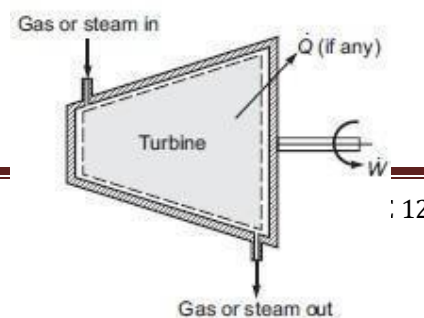
$$\dot{Q} - \dot{W}_x = \dot{m} \left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(Z_2 - Z_1) \right]$$

The above equation is known as the **steady flow energy equation (SFEE)** in terms of energy flow per unit time and is expressed in **J/s**.

In terms of energy flow per unit mass, the equation is given by,

$$q - w = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(Z_2 - Z_1), \text{ (J/kg)}$$

SFEE for Turbine and Compressor



For a turbine, if it is insulated and the flow velocities are small, the kinetic terms can be neglected.
Hence the SFEE is,

$$\dot{W}_x = \dot{m} (h_1 - h_2)$$

On the above equation, the work is done at the expense of enthalpy.

For a compressor, work done on the fluid is negative. Hence,

$$\dot{W}_x = \dot{m} (h_2 - h_1)$$

Second Law of Thermodynamics

Kelvin-Planck Statement

It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

Such a heat engine is called **perpetual motion machine of the second kind** or **PMM2**.

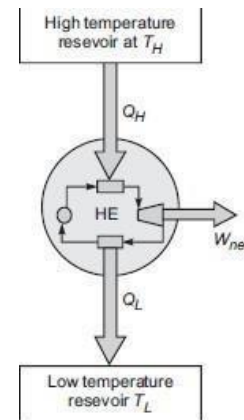
Clausius' Statement

It states that, it is impossible to construct a device which, operating in a cycle, will produce no effect other than the transfer of heat from a cooler to a hotter body.

Application of Second Law

Heat engine¹

- A heat engine is a device which operates in a cycle.
- It receives the heat energy from a high temperature reservoir, converts the heat energy into work and rejects the remaining heat to a low-temperature reservoir.
- The working of the heat engine can be described as follows,
 - a. It receives heat Q_1 from the high-temperature reservoir (source) at T_2 .
 - b. It converts the part of heat supplied into useful work as W_{net} .
 - c. It rejects the remaining heat Q to a low temperature reservoir (sink) at T_1 .
- The net work output of a heat engine is the difference between the total work done by the turbine and work input to feed pump, etc.



$$W_{net} = W_T - W_P$$

¹ From the fig., $T_H = T_1$ and $T_L = T_2$
And $Q_H = Q_1$ and $Q_L = Q_2$

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→ For any cyclic heat engine, the net work can also be obtained from the difference between heat supplied and heat rejection, i.e.

$$W_{net} = Q_1 - Q_2$$

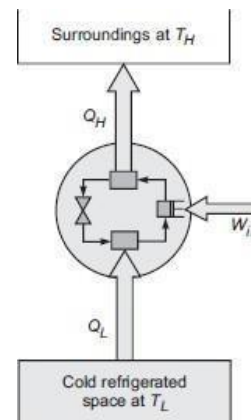
Thermal Efficiency: It is defined as the ratio of the desired output to the energy input. For a cyclic heat engine, the thermal efficiency is given by,

$$\eta_{th} = \frac{\text{Net Work Output}}{\text{Energy Input as Heat}} = \frac{W_{net}}{Q_1}$$

$$\begin{aligned}\eta_{th} &= \frac{Q_1 - Q_2}{Q_1} \\ &= 1 - \frac{Q_2}{Q_1}\end{aligned}$$

Refrigerator

- A refrigerator is a device operating in a cycle, which maintains a body at lower temperature than its surroundings.
- A refrigerator extracts heat continuously from a controlled space, and thus it is maintained at a lower temperature than its surroundings.
- The working fluid in the refrigerator is called the *refrigerant*.



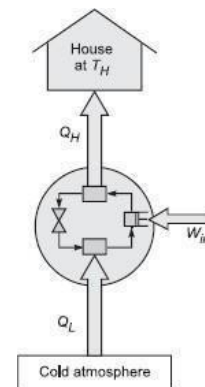
Coefficient of Performance of Refrigerator (COP)_R

- The performance of a refrigerator is measured in terms of the coefficient of performance (COP).
- It is defined as the ratio of the desired output (refrigerating effect) to the energy (work) input, i.e.

$$(COP)_R = \frac{\text{Refrigerating Effect}}{\text{Work Input}} = \frac{Q_2}{W}$$

Heat Pump

- A heat pump is a device, operating in a cycle, which maintains a space at a higher temperature than the surroundings.
- The heat pump supplies heat continuously to the controlled space, and thus maintained at a higher temperature than its surroundings.
- The heat pump absorbs the heat from low-temperature surroundings and supplies it to a higher temperature space at the cost of work input to the compressor.



COP of Heat Pump

$$\begin{aligned}(COP)_{HP} &= \frac{Q_1}{W} \\ &= \frac{Q_2 + W}{W}\end{aligned}$$

$$= 1 + \frac{Q_2}{W}$$

$$(COP)_{HP} = 1 + (COP)_R$$

PROPERTIES, PROCESSES OF PERFECT GAS

The ideal state refers to a state where all real gases behave in a similar manner. This condition is achieved when the absolute pressure of the gases approaches zero. This behaviour of real gases at an ideal state gives birth to the concept of ideal gas that behaves ideally at all pressures. An ideal gas must have the following characteristics:

1. No intermolecular forces of attraction or repulsion.
2. Does not change its phase during a thermodynamic process.
3. Must obey Boyle's law, Charles law and the characteristic gas equation.

Laws of Perfect Gas

Boyle's Law

→ It states that, the specific volume is inversely proportional to absolute pressure for a gas undergoing a constant temperature process, i.e.

$$v \propto \frac{1}{p}$$

or

$$pv = C$$

where C is the constant of proportionality.

→ For an ideal gas undergoing a constant temperature process from state 1 to state 2;

$$p_1 v_1 = p_2 v_2$$

→ Boyle's law represents a rectangular hyperbola curve on the p-v diagram. It is also referred to as an **isotherm**.

→ The process occurring at constant temperature is known as an **isothermal process**.

Charles's Law

→ It states that, the change in specific volume is directly proportional to the change in absolute temperature of gas undergoing a constant pressure process, i.e.

$$v \propto T$$

$$\frac{v}{T} = C$$

→ Where, C is the constant of proportionality at constant pressure.

→ For an ideal gas undergoing a constant pressure process from state 1 to state 2;

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$$\frac{v_1}{T_1} = \frac{v_2}{T_2}$$

→ Charles's law also states that the absolute pressure varies directly with absolute temperature for an ideal gas undergoing a constant volume process, i.e

$$p \propto T$$

$$\frac{p}{T} = C$$

→ Similarly, for an ideal gas undergoing a constant volume process,

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

Avogadro's Law

→ Avogadro's law states that, the molecular mass of all perfect gases occupies the same volume at NTP (i.e. 1 atm, 0°C).

→ The average volume for 1 kg mol of any perfect gas at N.T.P is 22.413 m³.

→ For a certain gas of mass m in kg and molecular weight μ , the number of 'kg mol' of the gas n , is given by,

$$n = \frac{m}{\mu} \text{ kg mol}$$

→ The molar volume, \bar{v} , is given by,

$$\bar{v} = \frac{V}{n} \text{ m}^3/\text{kgmol}$$

→ Where, V is the total volume of the gas in m³.

Equation of State

→ It is the functional relationship among the thermodynamic properties such as, pressure p , molar or specific volume v , and absolute temperature T .

→ It is expressed in the form,

$$f(p, v, T) = 0$$

→ If any of the two properties are specified, the third property can be determined by a functional relation, i.e.

$$p = f(v, T)$$

$$v = g(p, T)$$

$$T = h(p, v)$$

General Gas Equation

→ As for any thermodynamic system the properties vary simultaneously, the equation obtained by combining Boyle's and Charle's law is given by,

$$\begin{aligned} v &\propto \frac{T}{p} \\ v &= \frac{RT}{p} \\ pv &= RT \end{aligned}$$

→ Where, R is the **characteristic gas constant** or **specific gas constant**.

→ Hence the above relation is called the **characteristic gas equation** for an ideal gas or **ideal gas equation of state**.

Ideal Gas

Universal Gas Constant

→ From Avogadro's law, when $p = 760\text{mmHg} = 1.013 \times 10^5\text{N/m}^2$, $T = 273.15\text{ K}$, and $v = 22.4\text{ m}^3/\text{kgmol}$

$$\begin{aligned} R &= \frac{1.013 \times 10^5 \times 22.4}{273.15} \\ &= 8314.3\text{ Nm/kgmolK} \\ &= \mathbf{8.3143\text{ kJ/kgmolK}} \end{aligned}$$

→ Also,

$$\begin{aligned} R &= \frac{R}{\mu} \\ \text{or } R &= R\mu \end{aligned}$$

Characteristic Gas Constant

It is given by $R = \frac{R}{\mu}$, where μ is the molecular weight.

$$= \frac{8.3143}{32} = 0.262\text{ kJ/kgK}$$

For oxygen, R_{O_2}

$$= \frac{8.3143}{32} = 0.262\text{ kJ/kgK}$$

For air, R_{air}

$$= \frac{8.3143}{28.96} = 0.287\text{ kJ/kgK}$$

Specific Heats of Ideal Gas

Specific Heat at Constant Volume

→ It is defined as the amount of heat energy transferred to raise the temperature of unit mass of a substance through 1 degree at constant volume.

→ It is also defined as the ***change of specific internal energy of a substance per unit change in temperature at constant volume.***

→ It is given by the relation,

$$c_v = \left(\frac{\partial u}{\partial T} \right)_v$$

or, $du = c_v dT$

→ The above equation holds good for an ideal gas for any process. It's only true for any other substance undergoing a constant volume process.

→ c_v is a property.

→ It's unit is **J/kgK** or **kJ/kgK**

2.2.1 Specific Heat at Constant Pressure

→ It is defined as the amount of heat energy transferred to raise the temperature of unit mass of a substance through 1 degree at constant pressure.

→ It is also defined as the ***change of specific enthalpy of a substance per unit change in temperature at constant pressure.***

→ It is given by the relation,

$$c_p = \left(\frac{\partial h}{\partial T} \right)_p$$

or, $dh = c_p dT$

→ The above equation holds good for an ideal gas for any process. It's only true for any other substance undergoing a constant pressure process.

→ c_p is a property.

→ It's unit is **J/kgK** or **kJ/kgK**

Relation between Specific Heats

We know that, the enthalpy of any substance is given by,

$$h = u + pv$$

or, $h = u + RT$ (for an ideal gas)

Now, $dh = du + RdT$
 $= c_v dT + RdT$

$$= dh = (c_v + R)dT$$

Since, $dh = c_p dT$

Therefore, $c_p = c_v + R$

or, $c_p - c_v = R$

Also,

$$\frac{c_p}{c_v} = \gamma$$

$$c_p = \gamma c_v$$

Enthalpy of a Gas

Joule's law states that, the internal energy of an ideal gas is a function of temperature only, i.e.

$$u = f(T)$$

In differential form,

$$du = c_v dT$$

The change in specific internal energy for an ideal gas during a process 1-2, is

$$\Delta u = \int_1^2 c_v dT$$

or, $\Delta u = u_2 - u_1 = c_v(T_2 - T_1)$

The enthalpy per unit mass of an ideal gas is,

$$h = u + RT$$

Therefore, $h = f(T)$

In differential form,

$$dh = c_p dT$$

The change in specific enthalpy for an ideal gas during a process 1-2, is

$$\Delta h = \int_1^2 c_p dT$$

or, $\Delta h = h_2 - h_1 = c_p(T_2 - T_1)$

Application of 1st Law of Thermodynamics to Non Flow Process

The important non flow process commonly dealt in engineering applications is:

1. Constant-volume process

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2. Constant-pressure process
3. Constant-temperature process
4. Constant-entropy process
5. Polytropic process

Non-Flow Process	<i>p-v, T-s Diagram</i>	<i>Relation</i>	
Isochoric Process		Property Relations	$\frac{p_1}{T_1} = \frac{p_2}{T_2}$
		Work done	$W_{1-2} = 0$
		Heat Transferred	$Q = \int_1^2 C_v dT$ $= mc_v dT$ or, $q = c_v(T_2 - T_1) \text{ kJ/kg}$
		Change in Enthalpy	$\Delta h = c_p(T_2 - T_1) \text{ kJ/kg}$ $\Delta H = m\Delta h$ $= mc_p(T_2 - T_1) \text{ kJ}$
		Change in Internal Energy	$Q = \Delta U = mc_v(T_2 - T_1)$
Isobaric Process		Property Relations	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$
		Work done	$W = \int_1^2 p dV$ $W = p(V_2 - V_1) \text{ kJ}$
		Heat Transferred	$Q = \int_1^2 C_p dT$ $= mc_p(T_2 - T_1) \text{ kJ}$ $q = c_p(T_2 - T_1) \text{ kJ/kg}$
		Change in Enthalpy	$\Delta h = c_p(T_2 - T_1) \text{ kJ/kg}$ $\Delta H = mc_p(T_2 - T_1) \text{ kJ}$
		Change in Internal Energy	$\Delta U = mc_v(T_2 - T_1) \text{ kJ}$
Isothermal Process		Property Relations	$p_1 V_1 = p_2 V_2$
		Work done	$W_{1-2} = mRT \ln \left(\frac{V_2}{V_1} \right)$ $W_{1-2} = mRT \ln \left(\frac{p_1}{p_2} \right)$

Non-Flow Process	p-v, T-s Diagram	Relation	
		Heat Transferred	$Q_{1-2} = W_{1-2}$
		Change in Enthalpy	$\Delta h = \Delta H = 0$
		Change in Internal Energy	$\Delta U = 0$
Isentropic Process		Property Relations	$\frac{T_2}{T_1} = \left(\frac{v_2}{v_1}\right)^{1-\gamma} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$
		Work done	$W_{1-2} = \frac{mR(T_2 - T_1)}{1 - \gamma}$
		Heat Transferred	$Q_{1-2} = 0$
		Change in Enthalpy	$\Delta H = mc_p(T_2 - T_1)$
		Change in Internal Energy	$\Delta U_{1-2} = mc_v(T_2 - T_1)$
Polytropic Process		Property Relations	$\frac{T_2}{T_1} = \left(\frac{v_2}{v_1}\right)^{1-n} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$
		Work done	$W_{1-2} = \frac{mR(T_2 - T_1)}{1 - n}$
		Heat Transferred	-
		Change in Enthalpy	$\Delta H = mc_p(T_2 - T_1)$
		Change in Internal Energy	$\Delta U_{1-2} = mc_v(T_2 - T_1)$

INTERNAL COMBUSTION ENGINES

Explain and Classify IC Engines

An internal combustion engine is a machine that converts chemical energy in a fuel into mechanical energy.

Classification

According to piston strokes in the working cycle

1. Four stroke engine
2. Two stroke engine

According to the fuel used in the cycle

1. Petrol engine
2. Diesel engine
3. Gas engine
4. Multi fuel engine

According to method of ignition

1. Spark ignition
2. Compression ignition

According to fuel feeding system

1. Carbureted engine
2. Engine with fuel injection

According to charge feeding system

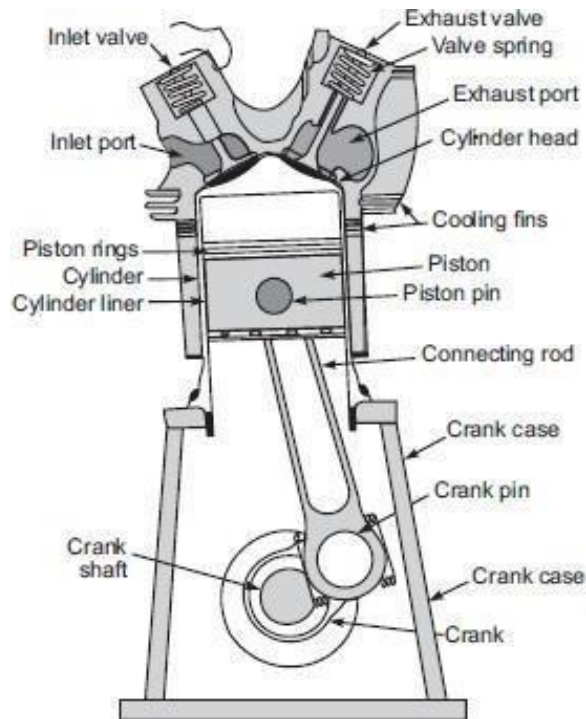
1. Naturally aspirated engine
2. Supercharged engine

According to cooling engine

1. Air cooled engine
2. Water cooled engine

According to the number of cylinders

1. Single cylinder engine
2. Multi cylinder engine



According to speed of the engine

1. Low speed engine
2. Medium speed engine
3. High speed engine

According to the position of engine

1. Horizontal engine
2. Vertical engine
3. V engine

Terminologies

Cylinder

- The engine cylinder is made from cast iron which provides with a cylinder liner on the inner side and a cooling arrangement on the outer side.
- For two stroke engines, it houses exhaust and transfer port.

Cylinder Head

- The top cover of the cylinder, towards TDC, is called cylinder head.
- It houses the spark plug in petrol engines and fuel injector in diesel engines.
- For four stroke cycle engines, the cylinder head has the housing of inlet and exhaust valves.

Piston

- It is the reciprocating member of the cylinder which is housed in the cylinder.
- It's usually made of cast iron or aluminium alloys.
- The top surface is called **piston crown** and bottom surface is called **piston skirt**.

Piston Rings

- The piston rings seal the space between the cylinder liner and piston in order to prevent leakage of high pressure gases, from cylinder to crank case.

Crank

- It is rotating member of the engine housed in the crank case.
- Its one end is connected with the crankshaft and the other end is connected with a connecting rod.

Crank Case: It is the housing of the crank and body of the engine.

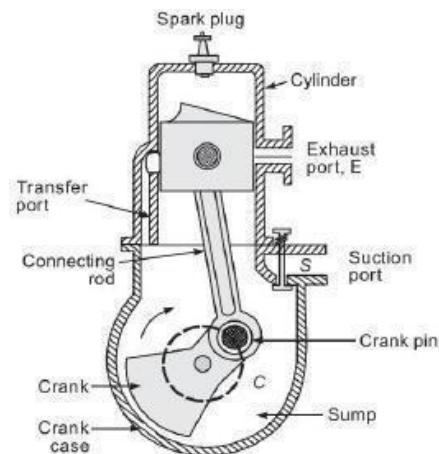
Connecting Rod

- The connecting rod transmits power developed on the piston to a crank shaft through crank.
- It's usually made of medium carbon steel.

Crank Shaft

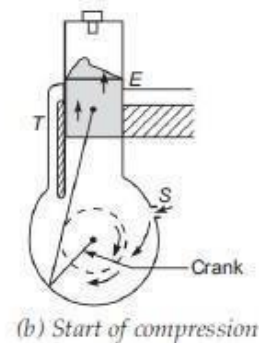
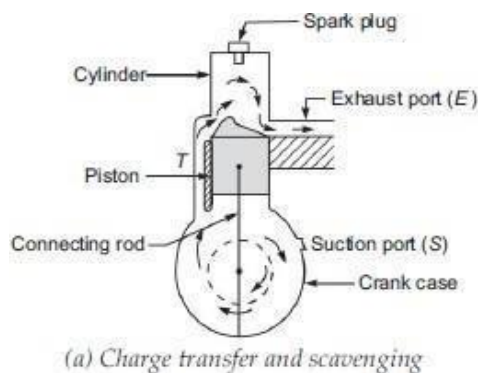
Working Principle of SI and CI Engines

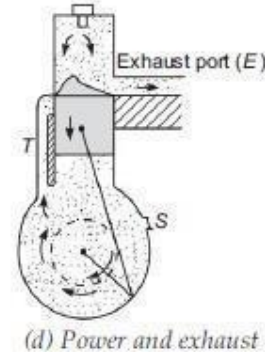
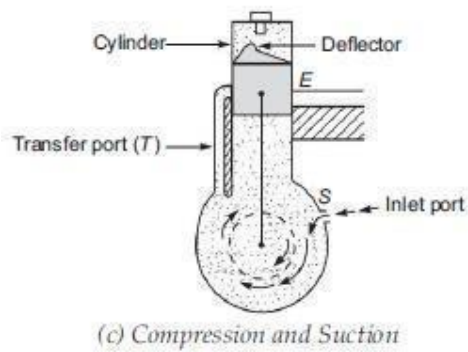
Two Stroke Petrol Engine



- Here essential operations are carried out in one revolution of the crankshaft or two strokes of the piston. Hence the engine is called two stroke or two stroke cycle engine.
- Construction
- it consists of a cylinder cylinder head piston piston rings connecting rod crank crankcase crankshaft et cetera
- The carburettor prepares the air fuel mixture outside the cylinder
- It consists of inlet and exhaust ports which are regulated by piston displacement.
- A suction pot with Reed type valve is used for induction of charge into the crankcase
- The transfer port is used for the transfer of charge from the crankcase to the cylinder
- the exhaust port discharges the burnt gases from the cylinder
- The spark plug is located in the cylinder head

Cycle of operation





The following operation takes place in a two stroke or in one revolution of the engine

Charge transfer and scavenging

- The transfer and exhaust ports are uncovered as the piston gets nearer to the crankcase.
- The compressed air fuel mixture from the crankcase enters through the transfer port and drives out the burnt gases of the previous cycle through the exhaust port.
- The piston top is made deflected so that the incoming charge is directed upwards and helps in expelling the burnt gases from the cylinder. This process is called scavenging

Compression and suction

- The transfer and exhaust port are covered by the piston and the charge gets compressed as the piston moves upward.
- Simultaneously a partial vacuum is created into the crankcase. The suction port opens by the crank movement allowing the fresh charge into the crankcase.

Combustion

- At the end of the stroke the piston reaches the top dead centre.
- A high intensity spark from the spark plug ignites the air fuel mixture thereby resulting in combustion.

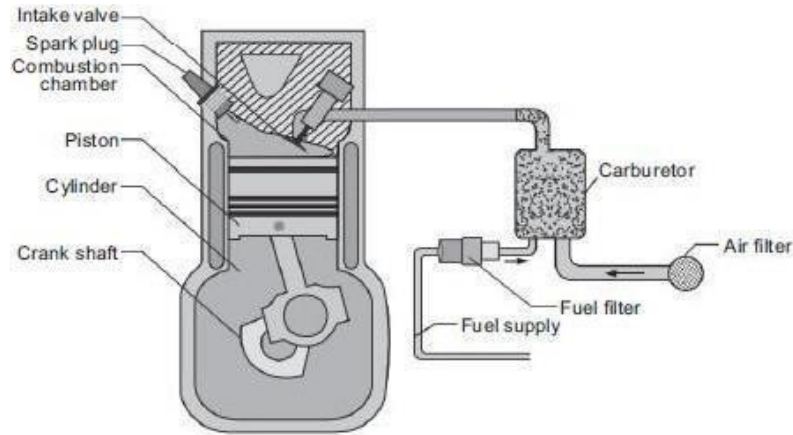
Power and exhaust

- The burning gases apply pressure on the top of the piston, and the piston is forced downward as a result of pressure generated.
- As the piston descends through about 80% of the expansion stroke, the exhaust port E is uncovered by the piston, and the combustion gases leave the cylinder by pressure difference.
- At the same time, the underside of the piston causes compression of charge taken into crank case.

Charging

- The slightly compressed charge in the crank case passes through the transfer port and enters the cylinder as soon as it is uncovered by the descending piston and when it approaches the bottom dead centre, the cycle is completed.

Four-Stroke Cycle Petrol Engine

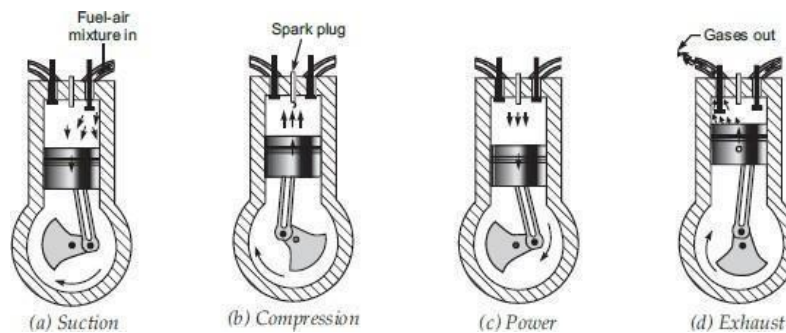


All operations are carried out in four strokes the piston, i.e., two revolutions of the crank. Therefore, the engine is called a four stroke engine.

Constructional Details

- Similar to a two-stroke engine, it also consists of a cylinder, cylinder head attached with spark plug, piston attached with piston ring, connecting rod, crank, crank shaft, etc.
- In a four-stroke engine, valves are used instead of ports. Those are suction and exhaust valves.
- These valves are operated by cams attached on a separate shaft, called a cam shaft. It is rotated at half the speed of a crank shaft.

Operation



The travel of the piston from one dead centre to another is called piston stroke and a four stroke cycle consists of four strokes as suction, compression, expansion and exhaust strokes.

Suction Stroke

- The suction valve opens, exhaust valve remains closed.
- The piston moves from the top dead centre to the bottom dead centre, the charge is drawn into the cylinder.

Compression Stroke

- When the piston moves from the bottom dead centre to top dead centre, and the suction valve is closed, exhaust valve remains closed.
- The trapped charge in the cylinder is compressed by the upward moving piston.
- As the piston approaches the top dead centre, the compression stroke completes.

Expansion Stroke

- At the end of the compression stroke, the compressed charge is ignited by a high intensity spark created by a spark plug, combustion starts and the high-pressure burning gases force the piston downward.
- The gas pressure performs work, therefore, it is also called working stroke or power stroke.
- When the piston approaches the bottom dead centre in its downward stroke then this stroke is completed. In this stroke, both valves remain closed.

Exhaust Stroke

- When the piston moves from the bottom dead centre to the top dead centre, only exhaust valve opens and burnt gases are expelled to surroundings by upward movement of the piston.
- This stroke is completed when the piston approaches the top dead centre. Thus, one cycle of a four stroke petrol engine is completed.
- The next cycle begins with piston movement from the top dead centre to the bottom dead centre.

DIESEL ENGINES

Two-stroke Diesel Engine

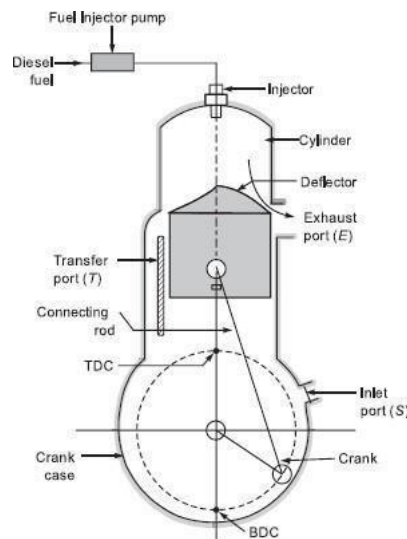
- The operation of a two-stroke Diesel engine is similar to a petrol engine, except it takes air as charge and fuel is injected at the end of the compression stroke.
- It uses a high compression ratio and hence the injected fuel is self ignited.

Operation

Both inlet and exhaust take place through the cylinder ports which are covered and uncovered by the piston.

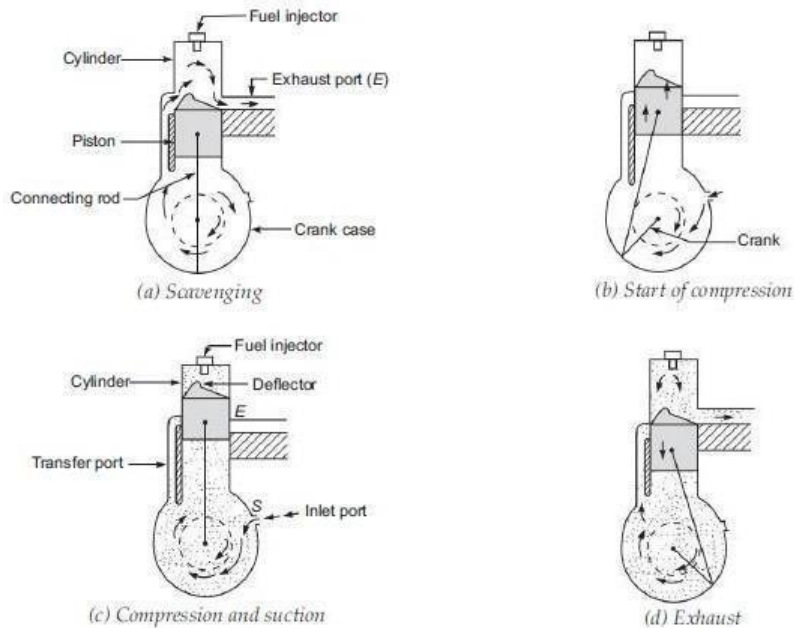
Charge Transfer and Scavenging

- When the piston is nearer to the crank case (bottom dead centre), the transfer port and exhaust port are uncovered by the piston.
- The slightly compressed air enters into the cylinder through the transfer port and helps to scavenge the remaining burnt gases from the cylinder.



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→ The charge transfer and scavenging continue till the piston completes its downward stroke and further, it moves upward and covers the transfer port.



Compression and Suction

→ After covering the transfer port, the exhaust port is also covered by the upward moving piston.

→ As both ports are covered by the piston, the air trapped in the cylinder is compressed during the forward stroke of the piston.

→ As the piston moves towards the cylinder head, a partial vacuum is created in the crank case, the inlet port opens and fresh air enters the crank case.

Combustion and Power

→ Near the end of the compression stroke, the fuel is injected at a very high pressure with the help of the fuel pump and injector.

→ The injected fuel is self ignited in the presence of hot air and combustion starts.

→ The piston is forced downward by very high pressure of burnt gases and power is transmitted to the crank shaft.

Exhaust

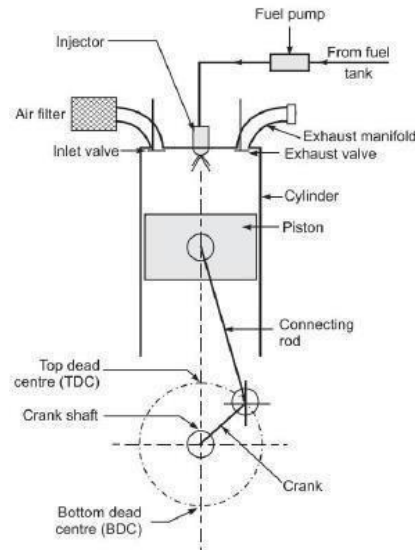
→ Near the end of the power stroke, the exhaust port is uncovered first by the piston and the products of combustion start leaving the cylinder as a result of pressure difference.

Charging

- The slightly compressed air in the crank case passes through the transfer port and enters the cylinder as soon as it is uncovered by the descending piston and when it approaches the bottom dead centres, the cycle is completed.

Four-stroke Diesel Engine

- A four-stroke Diesel engine contains a fuel injector, fuel pump, cylinder, cylinder head, inlet and exhaust valves, piston attached with piston rings, connecting rod, crank shaft, cams, camshaft, etc.
- One cycle of a four-stroke Diesel engine is completed in four strokes of the piston or two revolutions of the crank shaft



Suction Stroke

- The inlet (suction) valve opens, the exhaust valve remains closed, only air is drawn into the cylinder as the piston moves from the top dead centre to the bottom dead centre.
- This stroke ends as the piston approaches the bottom dead centre.

Compression Stroke

- As the piston moves from the bottom dead centre to the top dead centre, the inlet valve closes, exhaust valve remains closed.
- The air trapped into the cylinder is compressed in the cylinder till the piston approaches the top dead centre.
- The air temperature reaches about 800°C by compression.
- At the end of the compression stroke, the fuel is injected at very high pressure into the compressed hot air.
- The temperature of hot compressed air is sufficient to ignite the injected fuel.
- Thus, ignition takes place inside the cylinder.

Expansion Stroke

- During this stroke, both valves remain closed.
- The piston the top dead centre is pushed by expansion of burning gases.
- Actual work is obtained during this stroke due to the force obtained by high pressure burning gases.
- Therefore, this stroke is called power stroke or working stroke.

Exhaust Stroke

- During this stroke, the piston moves from the bottom dead centre to the top dead centre. The exhaust valve opens and the inlet valve remains closed.
- Burnt gases of the previous stroke are expelled out from the cylinder by the upward movement of the piston.

FUELS AND COMBUSTION

Define Fuel

A fuel is simply a combustible substance. It burns in the presence of oxygen and releases heat energy. The various types of fuels, like liquid, solid and gaseous fuels, are available for burning in boilers, furnaces and other combustion equipment.

Types of Fuel

Coal

- Coal is the most important solid fuel and its main constituent is carbon.
- It also contains some amount of oxygen, hydrogen, nitrogen, sulphur, moisture and ash.
- Coal is a mineral substance of vegetable origin.
- It is the result of decay of vegetable matter which accumulated under earth millions of years ago and got transformed by the action of heat and pressure.
- Its transformation occurs progressively and passes through different stages during its formation from vegetation.
- The stages are listed and discussed below:

1. Peat

- It is a spongy humidified substance and the first stage at which the fuel is derived from the wood and vegetable matter.
- It possesses constituents very nearest to those of wood with 30% moisture.
- It has lowest calorific value about 14,500 kJ/kg.
- It is mainly used as a fuel in gas-producer plants.
- Other varieties of coal are derived from peat.

2. Lignite

- It is next to peat and is a soft coal, composed mainly of volatile matter and moisture content with low fixed carbon of about 60%.
- Its appearance is brown and it contains high ash and low heating value.
- It is a low-grade fuel having a calorific value about 21, 000 kJ/kg.
- It is too brittle, and hence it is converted into briquettes, which can be easily handled. It burns with heavy smoke.

3. Bituminous Coal

- Its formation is next to lignite and has a shining black in appearance.

- It contains about 70% carbon and the remaining as a large percentage of volatile matter.
- It is easy to ignite and it burns with yellow smoky flames.
- It has an average calorific value of 31, 500 kJ/kg.
- It is used for producing producer gas.

4. Anthracite

1. It is the next generation of bituminous coal, and has the highest rank.
2. It is a hard coal composed of about 90% carbon with little volatile content and practically no moisture.
3. It is brittle and has a shining black lusture.
4. It burns without flame and smoke but is difficult to ignite.
5. It is non-cracking and has minimum ash, sulphur, volatile matter and moisture content.
6. It has highest heating value, approximately 36,000 kJ/kg.
7. It is used as fuel in steam power plants.

5. Wood Charcoal

- It is obtained by heating of wood up to a temperature of 280°C in the absence of atmospheric air.
- During this process, the volatile matter and water are expelled and the residue is charcoal.
- It is an excellent fuel but costly.
- Its calorific value is about 28,000 kJ/kg.

6. Coke

- It is obtained from bituminous coal by the carbonization process, i.e., the bituminous coal is heated strongly in the absence of air for 48 hours.
- Thus, the volatile matter present in the coal is driven off.
- Coke is dull black in colour, hard, brittle, and porous. It consists of 90 to 95% carbon, small quantities of sulphur, hydrogen, nitrogen and phosphorus.
- It is a smokeless and clear fuel.
- Its average calorific value is 32,500 kJ/kg.
- It is used in steam power plants, blast furnaces and gas producers.

7. Briquettes

- It is produced from finely grounded low-grade coal by the moulding operation.
- The coal powder is mixed with a suitable binder and pressed together to form blocks or briquettes.
- The binding material may be pitch, coal tar, crude oil or clay.
- By this method, the heating value of low-quality fuel is improved.

8. Pulverised Coal

- Crushed coal in fine powder form is called pulverized coal.
- During combustion, it floats and thus comes in better contact of air, improving the combustion efficiency.

- Pulverised coal has flexibility of control, complete combustion with less excess air and high flame temperature.
- Pulverised coal is used in cement industries and in furnaces.

Liquid Fuels

- Most liquid hydrocarbon fuels are a mixture of hydrocarbons that are derived from natural petroleum, called the crude oils.
- Some of these are gasoline, diesel, methanol, kerosene, and fuel oil.
- Within each classification, there is a variety of grades and each is the mixture of a large number of different hydrocarbons.
- For convenience, the composition of certain hydrocarbons in a fuel is represented by a single hydrocarbon.
- For an example, gasoline, a mixture of more than 40 hydrocarbons, is treated as octane C_8H_{18} , diesel as dodecane $C_{12}H_{26}$, methanol as CH_3OH .
- The light diesel oil, furnace oil and LSHS (low sulphur heavy stock) are predominantly used in industrial applications.

Gaseous Fuel

1. LPG

- Liquefied Petroleum Gas is mainly a mixture of propane and butane.
- It is a mixture of those hydrocarbons which are in gaseous phase at normal atmospheric pressure, but may be condensed to the liquid state at normal temperature, by the application of moderate pressures.
- LPG vapour is denser than air, butane is about twice as heavy as air and propane about 1.5 times as heavy as air.
- Consequently, the vapour may flow along the ground and into drains sinking to the lowest level of the surroundings and be ignited at a considerable distance from the source of leakage.

2. Natural Gas

- Natural gas contains methane as the main constituent and other gases in small amounts.
- Natural gas has high calorific value and it burns without smoke. It is lighter than air and disperses into air easily in case of leak.

3. Coal Gas

- It is obtained by the carbonization process of coal.
- The quality of coal gas depends on the quality of coal used and the temperature of carbonization.
- It contains mainly H_2 , CO and various hydrocarbons. Its calorific value is about 22,500 kJ/m³.
- It is used in towns for street lighting and domestic lighting purposes.

4. Producer Gas

→ Producer gas is obtained by partial combustion of coal, coke and charcoal in a mixed air stream.

→ Its manufacturing cost is low and it has a calorific value of about 6500 kJ/m³.

→ It is used in furnaces.

5. Water Gas

→ Water gas is a mixture of H₂ and CO and is produced by passing steam over incandescent coke.

→ Blast furnace gas is a by-product in the production of pig iron in the blast furnace. It is used to preheat the blast in the furnace.

→ It is used as fuel in metallurgical furnaces. It has calorific value of the order of 3700 kJ/m³.

6. Coke Oven Gas

→ It is obtained as a by-product during the formation of bituminous coal.

→ It is used for industrial heating and power generation application.

→ It has a calorific value of about 17,000 kJ/m³.

→ Carbon monoxide, coal gas, biogas, methane, ethane, are some gaseous fuels.

Heating Values of Fuel

→ The term heating value or 'calorific value' is most commonly used in conjunction with the combustion of fuel.

→ The calorific value of a fuel is defined as the amount of heat energy liberated by complete combustion of unit quantity of a fuel.

→ It is also called heating value of the fuel and it can also be considered as an absolute value of enthalpy of combustion. That is,

$$\text{calorific(heating)value} = |h_c|$$

→ The calorific value is measured in kJ/kg or kJ/kmol for solid and liquid fuels and kJ/m³ for gaseous fuels.

→ There are two aspects of relation for heat of formation (or reaction) and calorific value:

1. The calorific value of the fuel is the absolute value of enthalpy of formation (or reaction), but expressed per unit quantity of fuel (i.e., reactants) rather than the products.
2. By convention, the calorific value is positive, it has opposite sign convention to that for enthalpy of formation (or reaction).

Higher and Lower Calorific Value of Fuels

→ All fuels are hydrocarbons, thus their main constituents are carbon and hydrogen.

→ During the combustion process, carbon burns to carbon dioxide and hydrogen reacts with oxygen and forms water vapour.

→ The magnitude of the calorific value depends on the phase of water vapour in the combustion products.

- When combustion products are cooled to the reactant's temperature, the water vapour gets condensed and the heat of its vaporisation is recovered.
- The calorific value thus obtained is called the higher calorific value (HCV) or gross calorific value.
- The lower calorific value (LCV) or net calorific value is the amount of heat released by complete combustion of unit quantity of fuel, when the vapour carries its heat of vaporisation. It is obtained by deducting the heat necessary to form the vapour from hydrogen i.e.,

$$\text{Lower calorific Value (LCV)} = \text{HCV} - m_v h_{fg}$$

Where,

m_v = mass of water vapour formed per kg of air

h_{fg} = the heat of vaporisation of water at 25°C and 1 atm
= 2441.5 kJ/kgK

The calorific value is also related as

$$\text{HCV} = \text{LCV} + (nh)_{fg \text{ H}_2\text{O}} \quad \text{kJ/kg of fuel}$$

n = number of kmol/kg of H₂O

h_{fg} = the heat of vaporisation of water at 25°C and 1 atm

The two units of calorific value can be correlated as,

$$\text{Calorific Value of fuel in kJ/kg} = \frac{\text{Calorific Value of fuel in kJ/mol}}{\text{Molecular weight of fuel in kg/kmol}}$$

Thus, the calorific value in kJ/kg is obtained by dividing the calorific value in kJ/kmol by the respective molecular weight

4.4 Difference between petrol and Diesel Engines

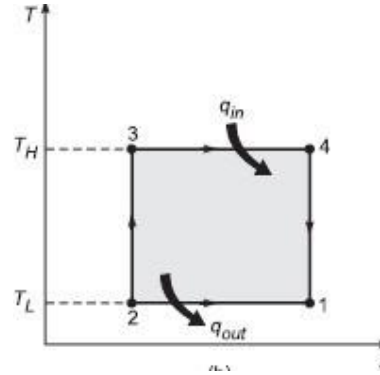
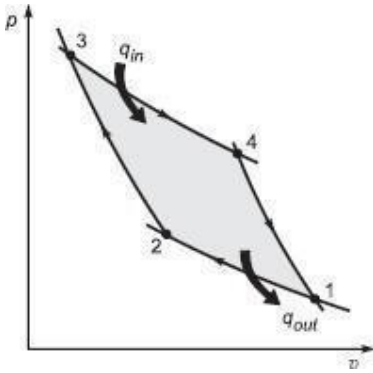
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<i>According to</i>	<i>Petrol Engine</i>	<i>Diesel Engine</i>
1. Basic cycle	It operates on constant-volume cycle.	It operates on constant-pressure cycle.
2. Fuel used	It uses gasoline or petrol as fuel.	It uses diesel and oils as a fuel.
3. Fuel induction	The air-fuel mixture is prepared in the carburettor and inducted into the engine cylinder during the suction stroke.	The Diesel engine takes in only air during the suction stroke, and it is compressed. At the end of the compression stroke the fuel is injected under the high pressure by a fuel injector.
4. Ignition of charge	The charge (air-fuel mixture) is ignited by a high-intensity spark produced at the spark plug.	Fuel is injected in very hot air, therefore, it is self-ignited.
5. Compression ratio	It uses less compression ratio, usually range of 4 to 10.	It uses high compression ratio, range of 14 to 21.
6. Pressure rise	Lower and controlled rate of pressure rise; therefore, operation is salient and smooth.	High rate of pressure variation, so engine operation is rough, and noisier.
7. Efficiency	For the same compression ratio, the efficiency of petrol engine is better.	It has lower efficiency for same compression ratio.
8. Pollution	Comparatively lower pollution for same power output.	Higher pollution for same power output.
9. Weight	It has comparatively less number of parts, thus is less in weight.	It uses large number of sturdier parts, thus engine is heavy.
10. Cost	Engines are cheaper.	Costlier engine due to complicated parts.
11. Maintenance	It requires less and cheaper maintenance.	It requires costlier and large maintainance.
12. Starting	Very easy to start due to lower compression ratio.	Very difficult to start due to higher compression ratio.

GAS POWER CYCLES

Carnot Cycle

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The Carnot cycle consists of four reversible processes,

1. Reversible isothermal expansion
2. Reversible adiabatic (isentropic) expansion
3. Reversible isothermal compression, and
4. Reversible adiabatic (isentropic) compression

Analysis

For process 1-2

$$Q_1 = p_1 V_1 \ln \left(\frac{V_2}{V_1} \right)$$

The work done during the process is,

$$W_{1-2} = Q_1 = mRT_1 \ln \left(\frac{V_2}{V_1} \right)$$

For process 2-3

Heat Transfer,

$$Q_{2-3} = 0$$

The work done on the gas,

$$W_{2-3} = \frac{p_3 V_3 - p_2 V_2}{\gamma - 1} = \frac{mR(T_1 - T_3)}{\gamma - 1}$$

For process 3-4

Heat rejection during the process,

$$Q_2 = p_3 V_3 \ln \left(\frac{V_4}{V_3} \right) = mRT_3 \ln \left(\frac{V_4}{V_3} \right)$$

The work done on the gas,

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$$W_{3-4} = Q_2 = p_3 V_3 \ln \left(\frac{V_3}{V_4} \right)$$

For process 4-1

Heat transfer during the process,

$$Q_{4-1} = 0$$

The work done on the gas,

$$W_{4-1} = \frac{p_1 V_1 - p_4 V_4}{\gamma - 1} = \frac{mR(T_1 - T_3)}{\gamma - 1}$$

Thermal Efficiency of the Carnot Engine

The efficiency for a Carnot engine is given by,

$$\eta_{th} = \frac{\text{Net Work done}}{\text{Heat Supplied}} = \frac{W_{net}}{Q}$$

For a cyclic heat engine,

$$W_{net} = Q_1 - Q_2$$

Therefore,

$$\begin{aligned} \eta_{th} &= \frac{Q_1 - Q_2}{Q_1} \\ &= 1 - \frac{Q_2}{Q_1} \end{aligned}$$

Also,

$$\eta_{th} = 1 - \frac{mRT_3 \ln(V_3/V_4)}{mRT_1 \ln(V_2/V_1)}$$

Considering the isentropic process 2-3

$$\begin{aligned} p_2 V_2^\gamma &= p_3 V_3^\gamma \\ \text{and} \quad \frac{T_1}{T_3} &= \frac{T_2}{T_3} = \left(\frac{V_3}{V_2} \right)^{\gamma-1} \end{aligned}$$

Similarly, for isentropic process 4-1,

$$\begin{aligned} p_1 V_1^\gamma &= p_4 V_4^\gamma \\ \text{and} \quad \frac{T_1}{T_3} &= \frac{T_1}{T_4} = \left(\frac{V_4}{V_1} \right)^{\gamma-1} \end{aligned}$$

Equating the above two equations, we get

$$\frac{V_3}{V_2} = \frac{V_4}{V_1}$$

and

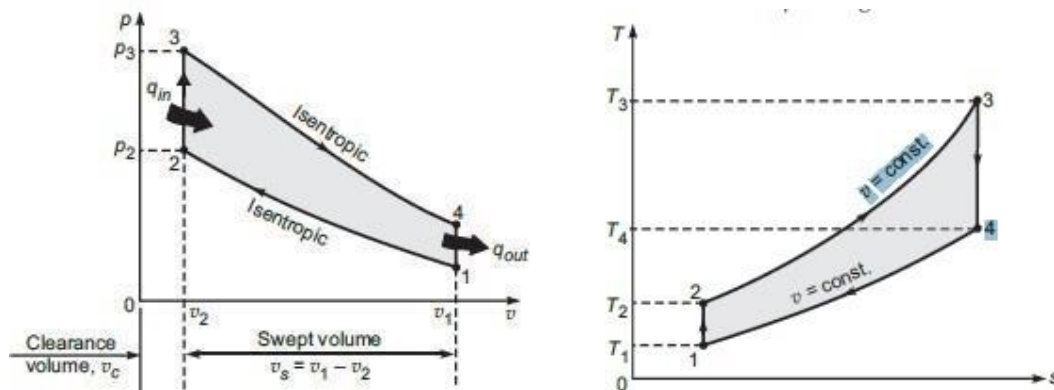
$$\frac{V_3}{V_4} = \frac{V_2}{V_1}$$

Therefore,

$$\eta_{th} = 1 - \frac{T_1}{T_3}$$

- The Carnot cycle efficiency is independent of the working substance.
- It depends on source and sink temperatures.
- The efficiency becomes maximum when, the sink temperature T_3 approaches zero. Since, it violates the Kelvin-Planck's statement in this condition, thus it is not possible.

Otto Cycle



- The Otto cycle is an ideal air standard cycle for the gasoline engine.
- The cycle consists of four processes:
 - a. **Process 1-2:** Isentropic Compression
 - b. **Process 2-3:** Reversible constant volume heat addition
 - c. **Process 3-4:** Isentropic Expansion
 - d. **Process 4-1:** Reversible constant volume heat rejection

Analysis

For Otto cycle, per unit mass of air

Heat supplied,

$$q_{in} = q_{2-3} = c_v(T_3 - T_2)$$

Heat rejected,

$$q_{out} = q_{4-1} = c_v(T_4 - T_1)$$

Net work done for a cycle is given by,

$$\begin{aligned} w_{net} &= q_{in} - q_{out} \\ &= c_v(T_3 - T_2) - c_v(T_4 - T_1) \end{aligned}$$

The thermal efficiency of the cycle,

$$\begin{aligned} \eta_{th} &= \frac{w_{net}}{q_{in}} \\ &= 1 - \frac{q_{out}}{q_{in}} \\ &= 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)} \\ &= 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \\ &= 1 - \frac{T_1 \left(\frac{T_4}{T_1} - 1 \right)}{T_2 \left(\frac{T_3}{T_2} - 1 \right)} \end{aligned}$$

Considering the isentropic process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1} = r^{\gamma-1}$$

Where, $r = \frac{v_1}{v_2}$, is called the compression ratio.

For the isentropic process 3-4,

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3} \right)^{\gamma-1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1} = r^{\gamma-1}$$

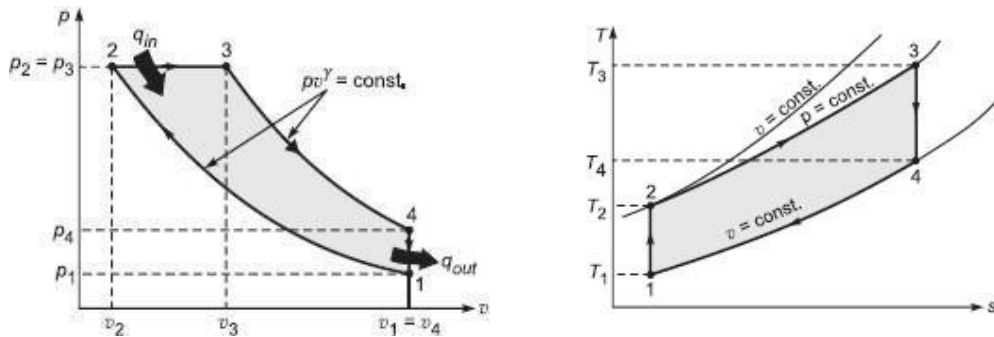
Hence, the efficiency is given by,

$$\begin{aligned} \eta_{Otto} &= 1 - \frac{T_1}{T_2} \\ &= 1 - \frac{1}{\frac{T_2}{T_1}} \\ \eta_{Otto} &= 1 - \frac{1}{(r)^{\gamma-1}} \end{aligned}$$

The ratio of specific heats (γ) is assumed to be constant and hence the efficiency for Otto cycle is the function of compression ratio only.

The Otto cycle efficiency increases with increase in temperature.

Diesel Cycle



- In petrol engines, the air-fuel mixture is compressed during the compression stroke, and thus the compression ratio is limited by engine knock.
- In case of Diesel engines, the air is compressed during the compression stroke, thus eliminating the possibility of auto-ignition.
- The Diesel engines are designed to operate at high compression ratios (i.e. between 12 and 24)
- The processes included in the Diesel cycle are:
 - a. **Process 1-2:** Isentropic Compression
 - b. **Process 2-3:** Reversible constant pressure heat addition
 - c. **Process 3-4:** Isentropic Expansion
 - d. **Process 4-1:** Reversible constant volume heat rejection

Analysis

For 1 kg mass of air undergoing a Diesel cycle,

Heat supplied,

$$q_{in} = q_{2-3} = c_p(T_3 - T_2)$$

Heat rejected,

$$q_{out} = q_{4-1} = c_v(T_4 - T_1)$$

Net work done for a cycle is given by,

$$\begin{aligned} w_{net} &= q_{in} - q_{out} \\ &= c_p(T_3 - T_2) - c_v(T_4 - T_1) \end{aligned}$$

The thermal efficiency of the cycle,

$$\eta_{th} = \frac{w_{net}}{q_{in}}$$

$$\begin{aligned}
 &= 1 - \frac{q_{out}}{q_{in}} \\
 &= 1 - \frac{c_p(T_4 - T_1)}{c_v(T_3 - T_2)} \\
 \eta_{Diesel} &= 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}
 \end{aligned}$$

The efficiency of the Diesel cycle can also be expressed in terms,

- a. Compression ratio: $r = \frac{V_1}{V_2} = \frac{v_1}{v_2} = \frac{\text{Volume before comprssion}}{\text{Volume after compression}}$
- b. Cut-off ratio: $\rho = \frac{V_3}{V_2} = \frac{v_3}{v_2} = \frac{\text{Volume after expansion}}{\text{Volume before expansion}}$
- c. Expansion ratio: $r_e = \frac{V_4}{V_3} = \frac{v_4}{v_3} = \frac{\text{Volume after expansion}}{\text{Volume before expansion}}$

It can be proved that

$$r = r_e \rho = \left(\frac{v_4}{v_3} \times \frac{v_3}{v_2} = \frac{v_1}{v_2} = r \right) |$$

Now for isentropic process 1-2,

$$\begin{aligned}
 \frac{T_2}{T_1} &= \left(\frac{v_1}{v_2} \right)^{\gamma-1} = r^{\gamma-1} \\
 T_2 &= T_1 r^{\gamma-1}
 \end{aligned}$$

Where, $r = \frac{v_1}{v_2}$, is called the compression ratio.

For constant pressure heat addition process 2-3,

$$\frac{T_3}{T_2} = \frac{v_3}{v_2} = \rho$$

$$T_3 = \rho T_2 = \rho r^{\gamma-1} T_1$$

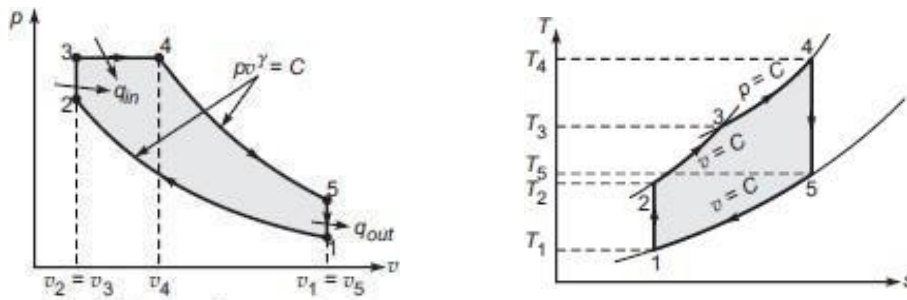
For the isentropic process 3-4,

$$\begin{aligned}
 \frac{T_4}{T_3} &= \left(\frac{v_3}{v_4} \right)^{\gamma-1} \\
 &= \left(\frac{1}{r_e} \right)^{\gamma-1} \\
 T_4 &= \left(\frac{\rho}{r_e} \right)^{\gamma-1} T_3 \\
 &= \left(\frac{\rho}{r_e} \right)^{\gamma-1} \rho r^{\gamma-1} T_1 \\
 T_4 &= \rho^{\gamma} T_1
 \end{aligned}$$

Using the value of T_2 , T_3 , and T_4 and putting in the efficiency relation, we get

$$\begin{aligned}\eta_{Diesel} &= 1 - \frac{(\rho^\gamma T_1 - T_1)}{\gamma(\rho r^{\gamma-1} T_1 - T_1 r^{\gamma-1})} \\ &= 1 - \frac{(\rho^\gamma - 1) T_1}{\gamma(\rho r^{\gamma-1} - r^{\gamma-1}) T_1} \\ \eta_{Diesel} &= 1 - \frac{1}{r^{\gamma-1}} \left[\frac{\rho^\gamma - 1}{\gamma(\rho - 1)} \right]\end{aligned}$$

Dual Cycle



→ Since the air standard Diesel cycle does not simulate the exact pressure-volume variation in a compression ignition engine, as the fuel injection starts before the end of compression stroke, the variation is approximated in the form of limited pressure cycle. Such a cycle is referred as **dual cycle** or **mixed cycle**.

→ Here some part of heat is added to air at constant volume, and the remainder at constant pressure.

Analysis

Heat supplied,

$$q_{in} = c_v(T_3 - T_2) + c_p(T_4 - T_3)$$

Heat rejected,

$$q_{out} = c_v(T_5 - T_1)$$

So, efficiency is given by,

$$\eta_{dual} = 1 - \frac{(T_5 - T_1)}{\left(\frac{T_3 - T_2}{\gamma} + \frac{T_4 - T_3}{\gamma} \right)}$$

The efficiency of Dual cycle can be expressed considering the following ratios;

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Compression ratio, $r = \frac{v_1}{v_2}$

Cut-off ratio, $\rho = \frac{v_4}{v_3}$

Pressure ratio, $= \frac{p_3}{p_2}$

Expansion ratio, $r_e = \frac{v_5}{v_4}$

For isentropic process 1-2,

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

For constant volume process 2-3,

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

$$T_3 = r_p r^{\gamma-1} T_1$$

For constant pressure process 3-4,

$$\frac{v_4}{T_4} = \frac{v_3}{T_3}$$

$$T_4 = \frac{v_4}{v_3} T_3 = \rho T_3$$

$$= \rho r^{\gamma-1} T_1$$

For isentropic expansion process 4-5,

$$\frac{T_5}{T_4} = \left(\frac{v_4}{v_5} \right)^{\gamma-1}$$

$$= \left(\frac{1}{r_e} \right)^{\gamma-1}$$

$$T_5 = \left(\frac{\rho}{r} \right)^{\gamma-1} T_4$$

$$T_5 = \left(\frac{\rho}{r} \right)^{\gamma-1} \rho r^{\gamma-1} T_1$$

$$T_5 = \rho^{\gamma} r_p T_1$$

Using the value of T_2 , T_3 , T_4 , and T_5 and putting in the efficiency relation, we get

$$\eta_{dual} = 1 - \frac{T_1(\rho^{\gamma} r_p - 1)}{T_1(r_p r^{\gamma-1} - r^{\gamma-1}) + \gamma T_1(\rho r_p r^{\gamma-1} - r_p r^{\gamma-1})}$$

$$\eta_{dual} = 1 - \frac{1}{r^{\gamma-1}} \left[\frac{\rho^{\gamma} r_p - 1}{(r_p - 1) + \gamma r_p (\rho - 1)} \right]$$

Therefore, the efficiency of Dual cycle is a function of r , ρ , r_p , and γ .

When,

→ $r_p = 1$, then $\eta_{dual} = \eta_{Diesel}$

→ $\rho = 1, r_p = 1, \eta_{dual} = \eta_{Otto}$

→ For same compression ratio and cut-off ratio, as pressure r_p increases, η_{dual} increases