MECHANICAL ENGINEERING SCIENCE (UE24ME141A)

Srinivasa Prasad K S

Department of Mechanical Engineering

MECHANICAL ENGINEERING SCIENCE

Unit1

Srinivasa Prasad K S
Department of Mechanical Engineering

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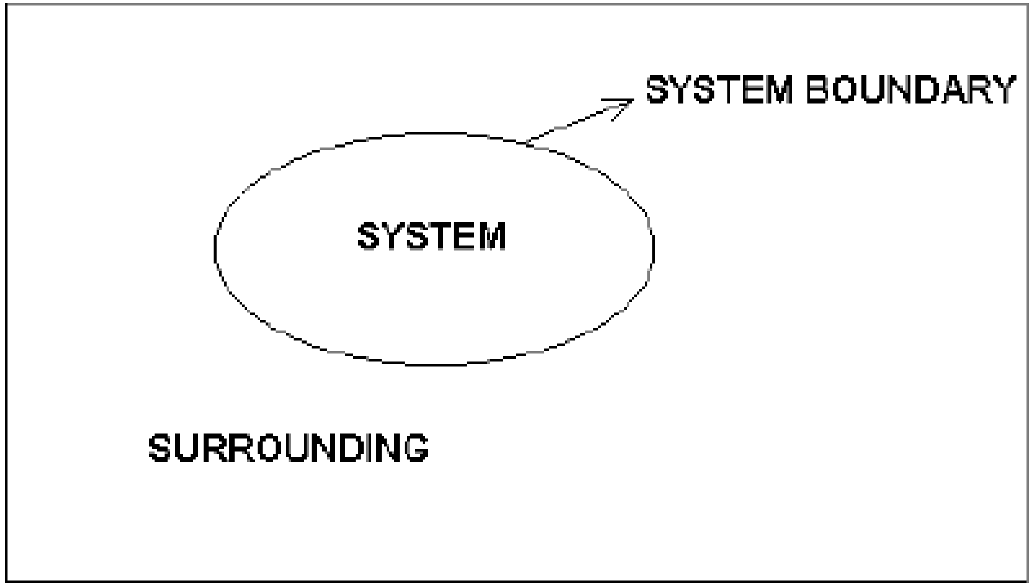
Chapter 1 – Basic Principles of Thermodynamics and Fluid Energy

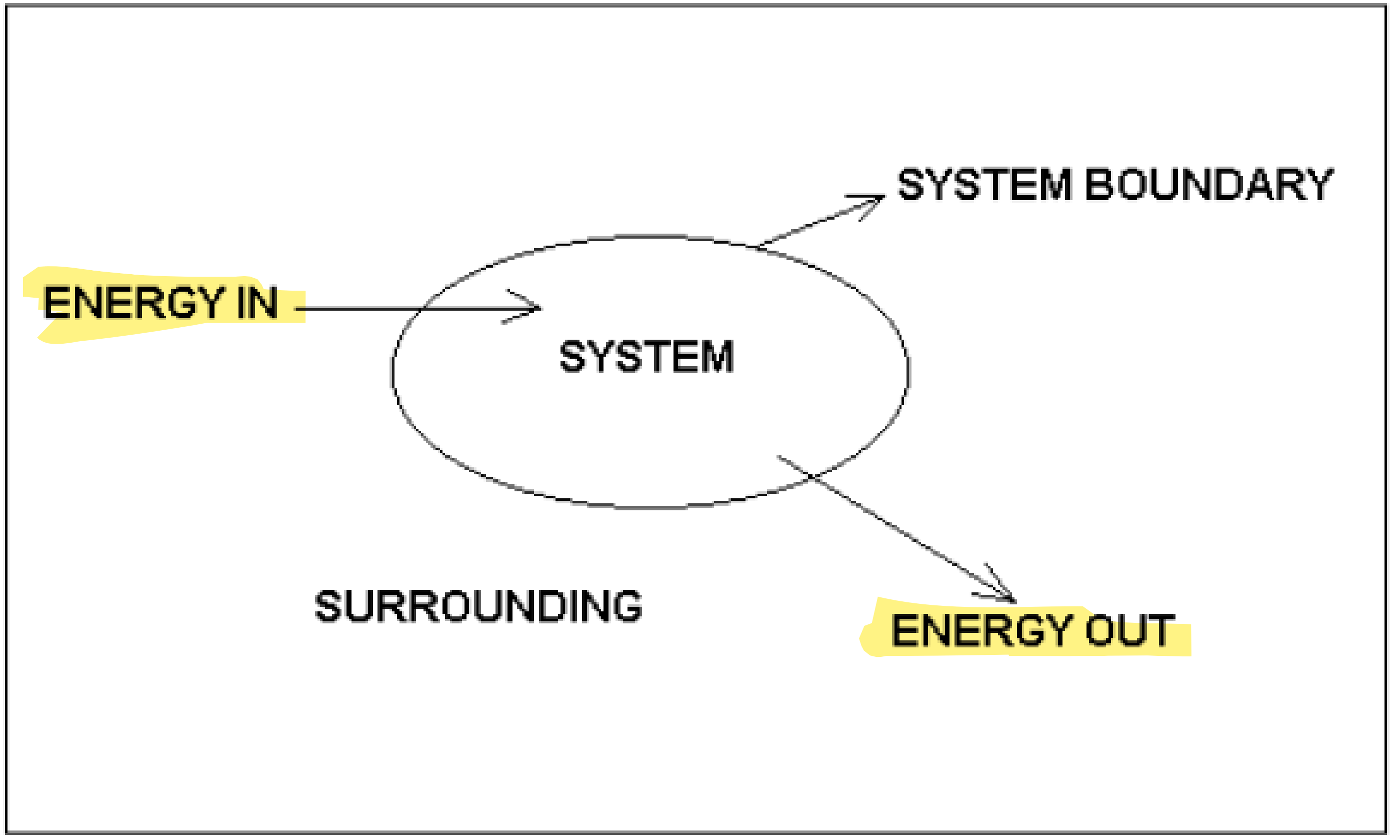
Srinivasa Prasad K S
Department of Mechanical Engineering
Courtesy: Dr. V Krishna, Department of Mechanical Engineering

System, Boundary and Surroundings

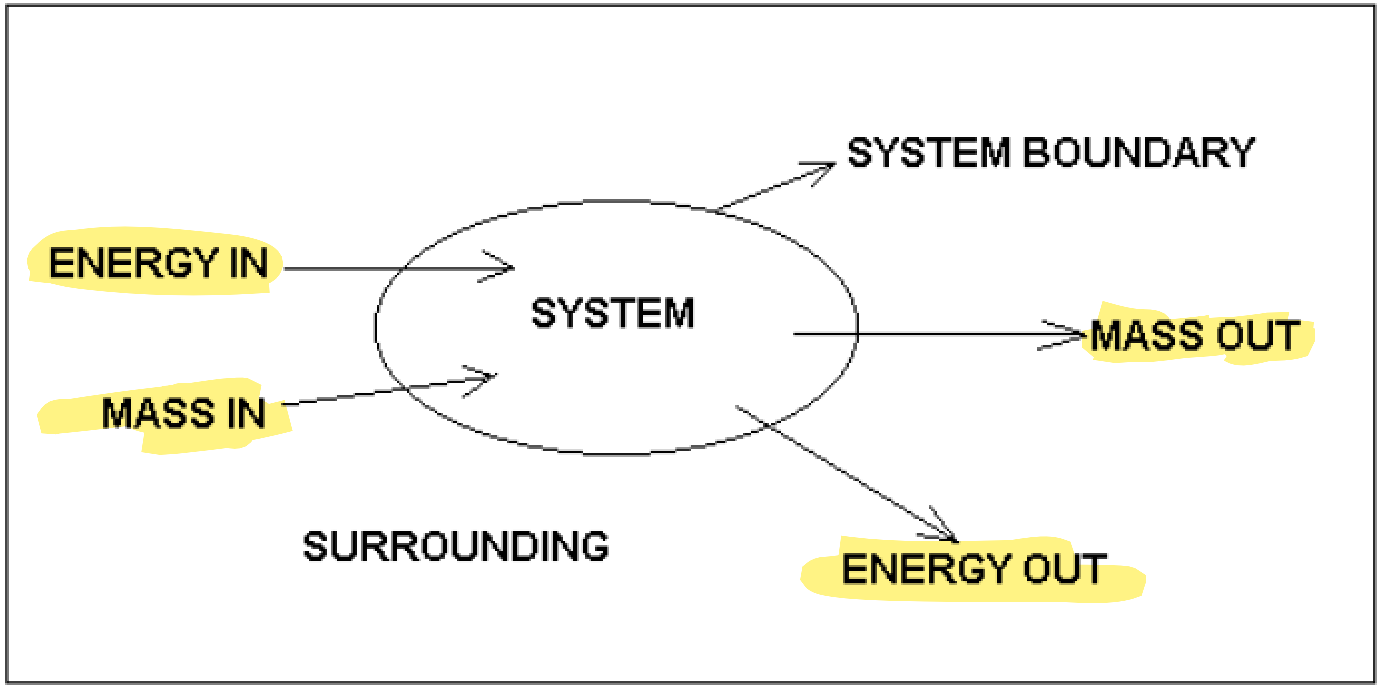
1. Thermodynamic System
2. Surroundings
3. Boundary
4. Universe



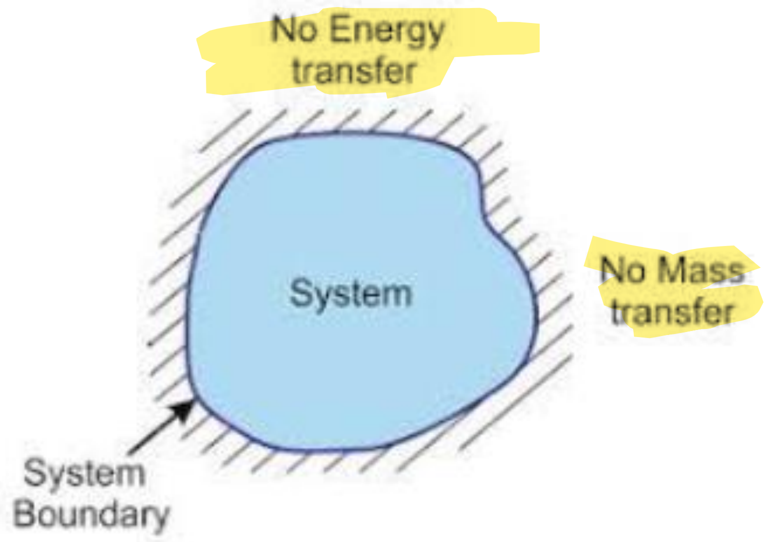
Closed System

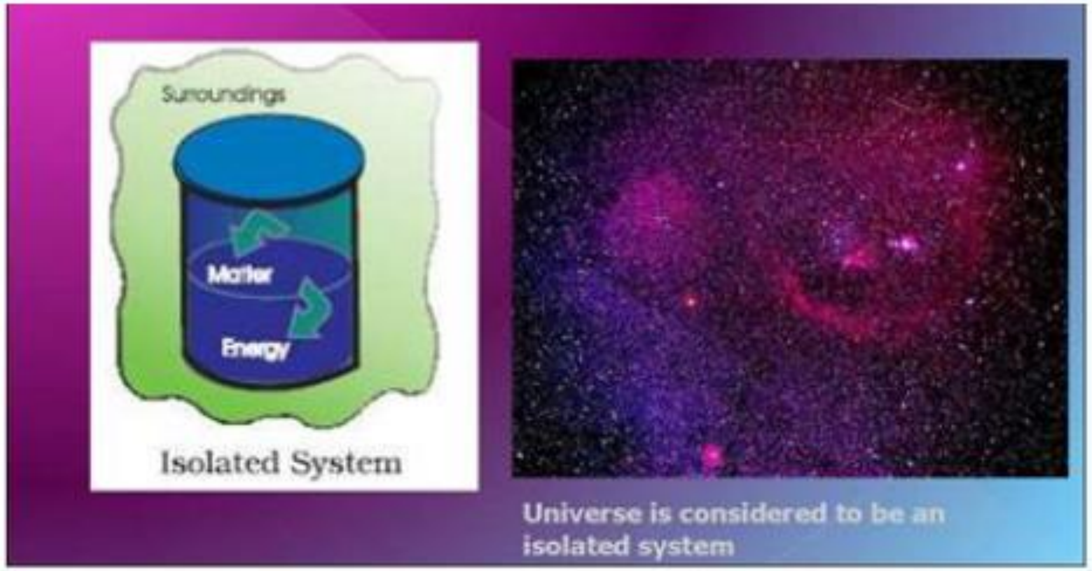


Open System


SYSTEM BOUNDARY
ENERGY IN
SYSTEM
MASS OUT
MASS IN
SURROUNDING
ENERGY OUT

Isolated System



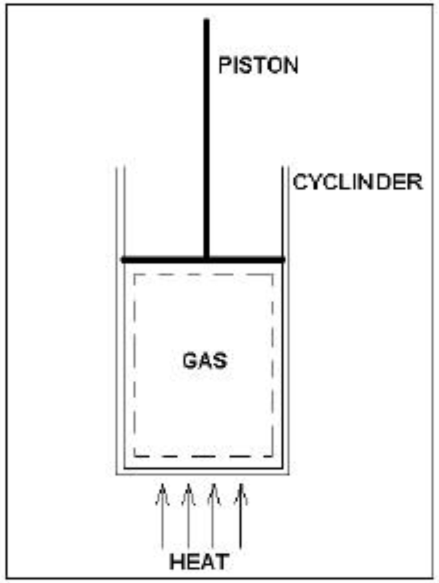


Can you recognize and classify the following as closed, open and isolated systems?

Electric Bulb

Centrifugal Pump

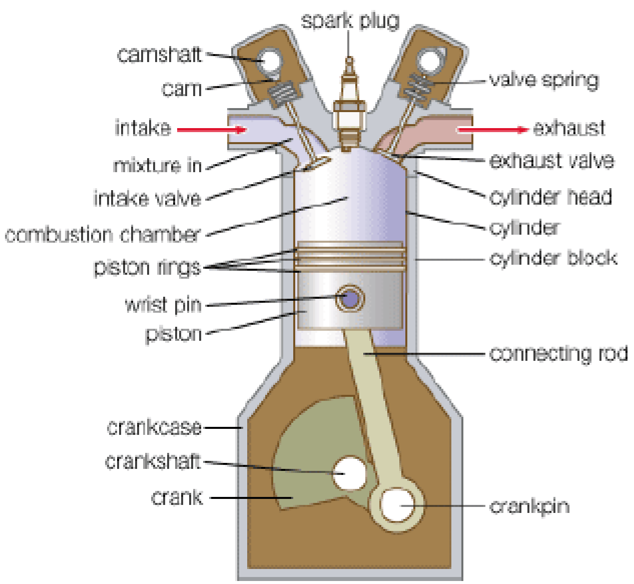
Can you recognize and classify the following as closed, open and isolated systems?



Gas in a piston-cylinder enclosure

Thermos Flask

Can you recognize and classify the following as closed, open and isolated systems?



IC Engine

Electric Stove

Can you recognize and classify the following as closed, open and isolated systems?

Air Compressor

Refrigerator

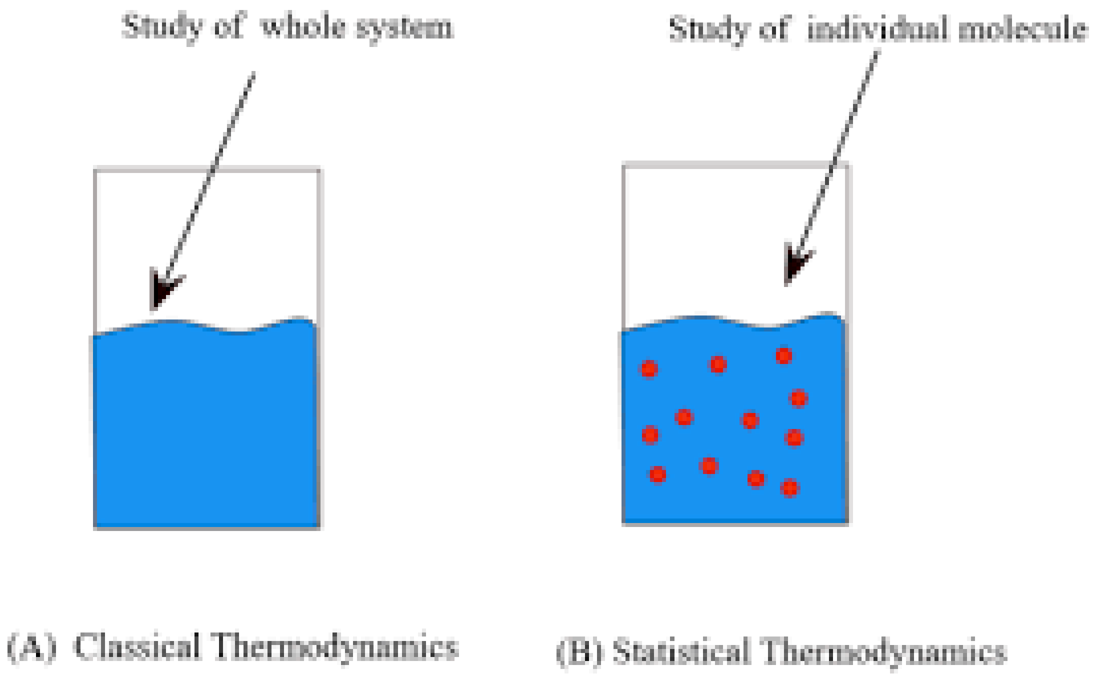
Macroscopic study

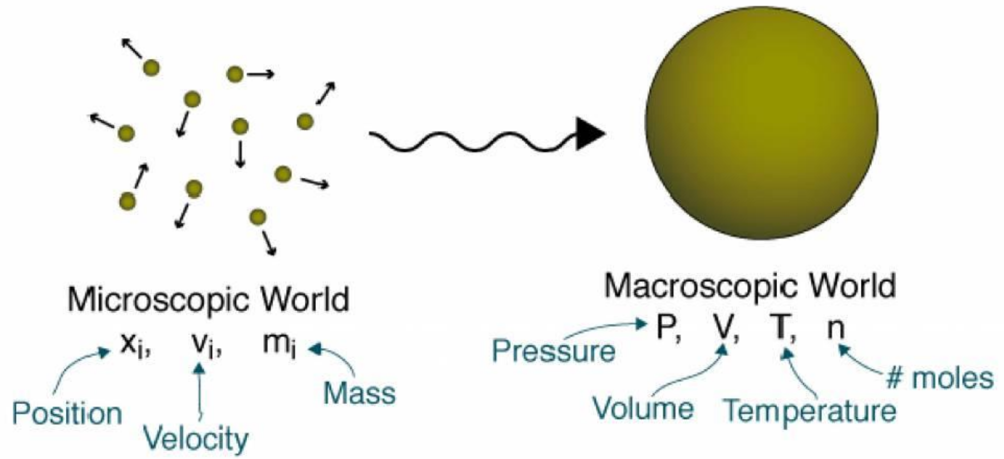
- This is the study and analysis of systems taking the entire mass of the system as a whole.
- The branch of thermodynamics that deals with such a study is called **classical thermodynamics**.

Microscopic study

- In this, the study and analysis of systems is made at a molecular level taking into consideration the effect of individual molecules on the behaviour of the system.
- The branch of thermodynamics that deals with such a study is called **statistical thermodynamics.**

Macroscopic and Microscopic Study





Concept of continuum

- Continuum seeks to define matter as a continuous nonspatial whole or extent or succession in which no part or portion is distinct or distinguishable from adjacent parts.
- Matter is treated as a continuum as though there are no intermolecular spaces

- **Any material, solid, liquid or gas is composed of billions of individual molecules, in a very small region, separated by empty spaces in between them. The continuum assumption considers that matter is continuously distributed and fills the entire region of the space it occupies.**

State of a system

- It refers to the condition of the system at any given instant of time.

Properties of a system

- These are the observable characteristics of a system that can be used to define the state of the system.

Intensive and Extensive Properties

Intensive properties

- These are the properties that are independent of the mass of a system. E.g. temperature, pressure

Extensive properties

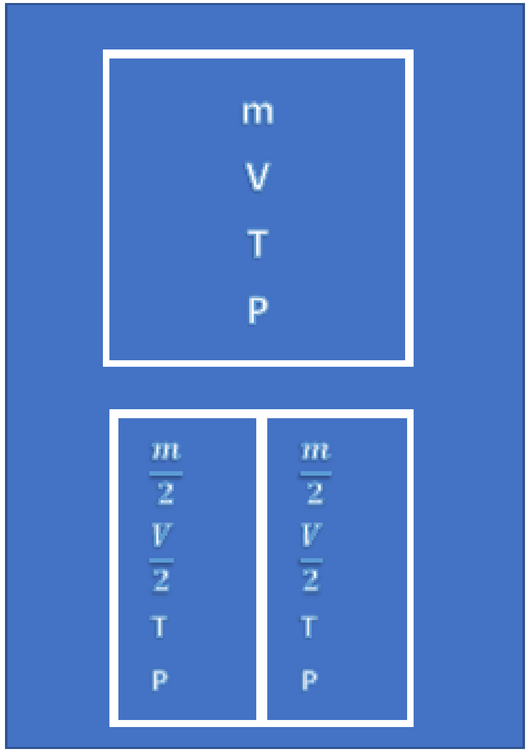
- These are the properties that are dependent on the mass of a system. E.g. volume, mass

Important Observations

- Value of intensive properties is the same at all points in a system.
- Value of an extensive property for a system is the sum of the values of the property at different points.

Intensive and Extensive Properties

When a system is divided into two equal parts its extensive properties in each part will be one half of the value for the undivided part, where as the value of intensive properties remain unchanged



Thermodynamic Equilibrium

Equilibrium refers to a state of balance within the system and between the system and its surroundings.

A system is said to be thermodynamic equilibrium when no change in macroscopic property is observed after it is isolated from its surroundings.

Such a system has to possess the following types of equilibria: -

1. Mechanical Equilibrium
2. Chemical Equilibrium
3. Thermal Equilibrium
4. Other Equilibria such as Electrical Equilibrium, Phase Equilibrium etc.

Thermodynamic Equilibrium

Thermodynamic equilibrium is a state where a system's properties don't change over time, unless an external force is applied.

1. Gas in a cylinder with a movable piston: When the temperature and pressure inside the cylinder are in equilibrium, the gas is in thermodynamic equilibrium.
2. Hot food

When hot food is left out, it exchanges heat with the air until both are at the same temperature.

3. Cup of hot tea

When a cup of hot tea is left out, the temperature of the tea eventually matches the temperature of the surrounding air.

Process

When a system undergoes a change of state, it is said to have undergone a process. During a process, it is implicit that the system is not in a state of thermodynamic equilibrium.

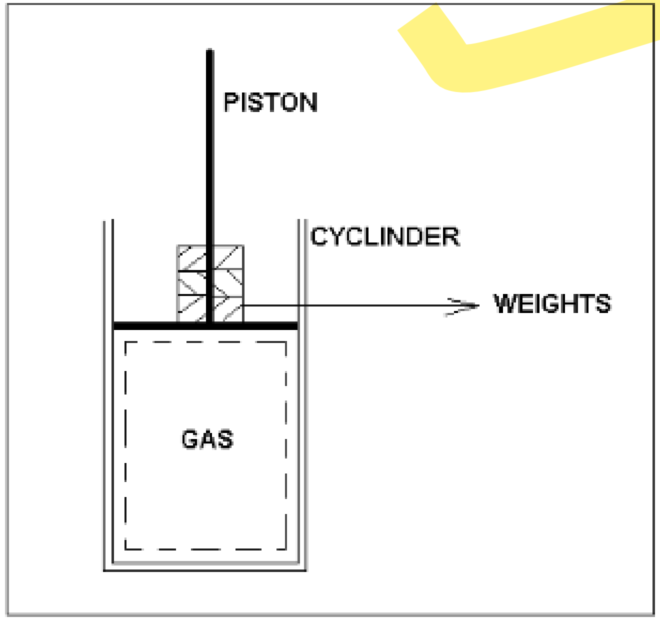
When a process takes place, the values of the properties change.

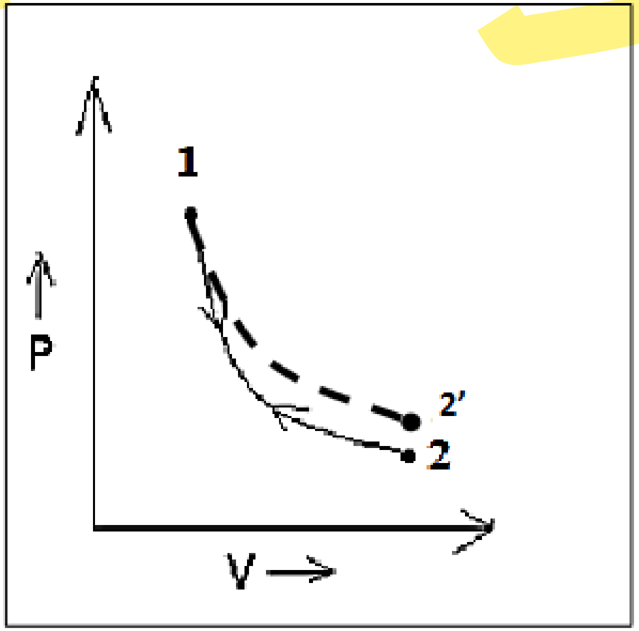
However, during a process, one or more properties of the system may remain constant. This makes the process distinct and gives it a name: -

- ✓ isothermal process – temperature remains constant
- ✓ Isobaric process– pressure remains constant
- ✓ Isochoric process – volume remains constant
- ✓ Isentropic process – entropy remains constant.

Quasi static or Quasi Equilibrium Process

Quasi – Static or Quasi – Equilibrium process is a process during the course of which deviation from thermodynamic equilibrium is negligibly small.





1-2: Quasi-static Process
1–2’: Real Process

Quasi static or Quasi Equilibrium Process

In thermodynamics, a quasi-static process, also known as a quasi-equilibrium process ,is a thermodynamic process that happens slowly enough for the system to remain in internal physical (but not necessarily chemical) thermodynamic equilibrium

Temperature is a measure of the hotness or coldness of a system

Since hotness or coldness is a highly relative term, temperature cannot be measured in an absolute sense.

To overcome this, we define equality of temperature or thermal equilibrium.

Equality of Temperature

Two systems or a system and its surrounding are said to have equality of temperature if there is no change in any observable property when they are brought into thermal contact.

Equality of Temperature

Hot block reduces the temperature and decrease in length.

Cold block increase the temperature and increase in length.

Electrical resistance reduces from hot to cold.

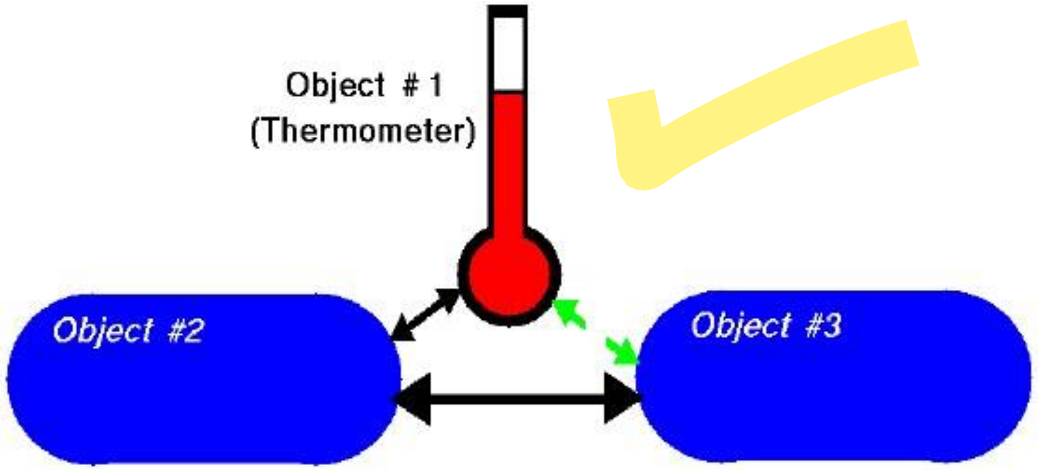
Equality of Temperature

3. When a mercury thermometer is brought into contact with these blocks, the level of mercury decreases when in contact with the heated block, while it decreases when in contact with the cold block.

Similarly, many more changes may be observed. After some time, all thee change cease to exist. At this stage, we may say that the two blocks have equality of temperature or they are in thermodynamic equilibrium.

Zeroth Law of Thermodynamics

"When two systems, say A and B are independently in thermal equilibrium with a third system, say C, then they are in thermal equilibrium with each other. "



When two objects are separately in thermodynamic equilibrium with a third object, they are in equilibrium with each other.

Objects in thermodynamic equilibrium have the same temperature.

Zeroth Law of Thermodynamics

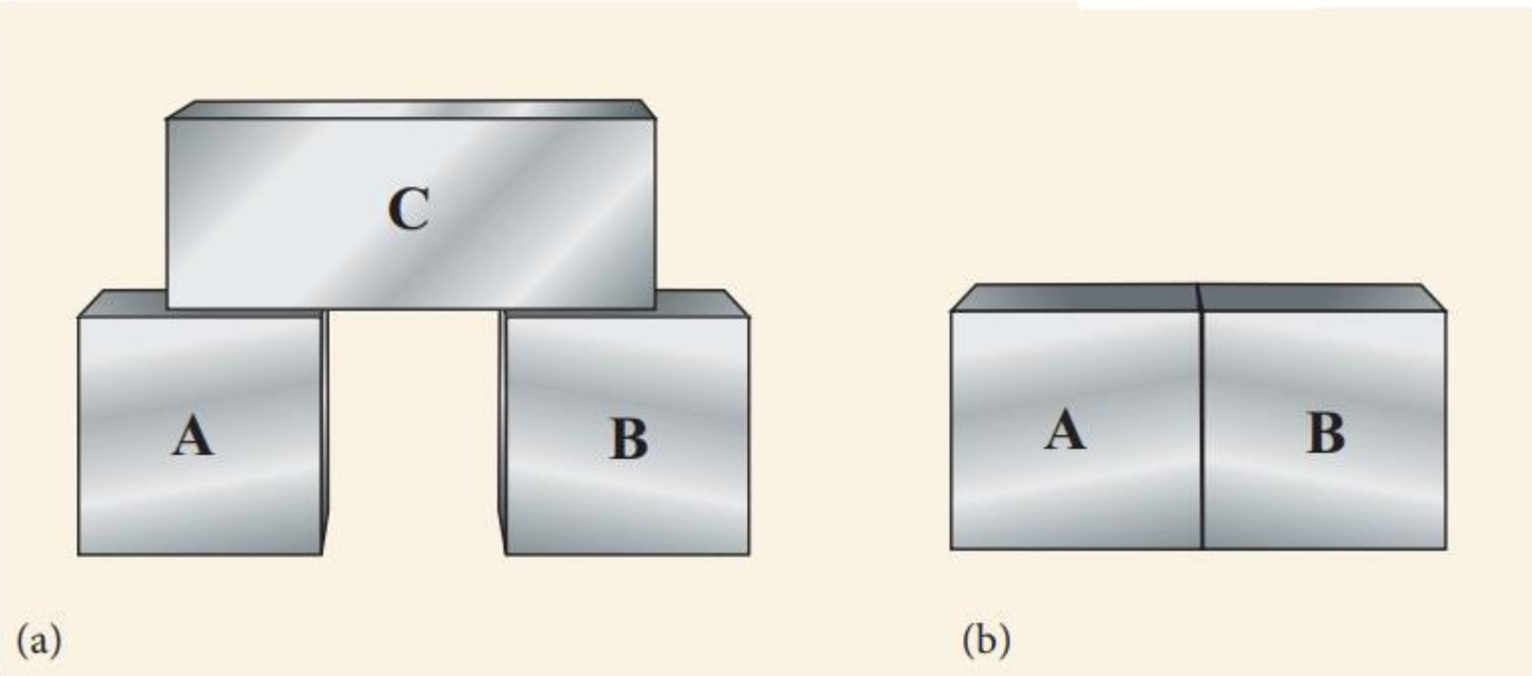
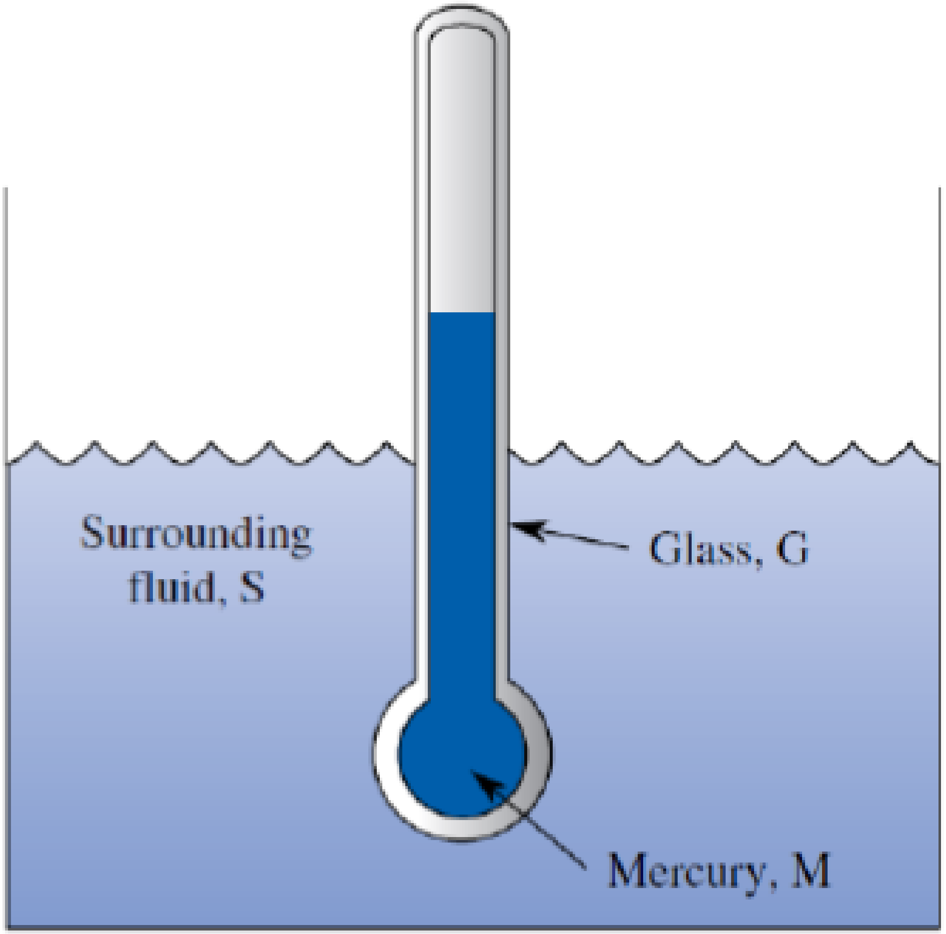


Figure 8.18 (a) Two systems A and B in thermal contact with object C separately (b) If systems A and B are in thermal contact, they are also in thermal equilibrium with each other.

Illustration of Zeroth Law of Thermodynamics as basis for Temperature Measurement



Zeroth law;

$T_G = T_S$

and

$T_M = T_G$

therefore,

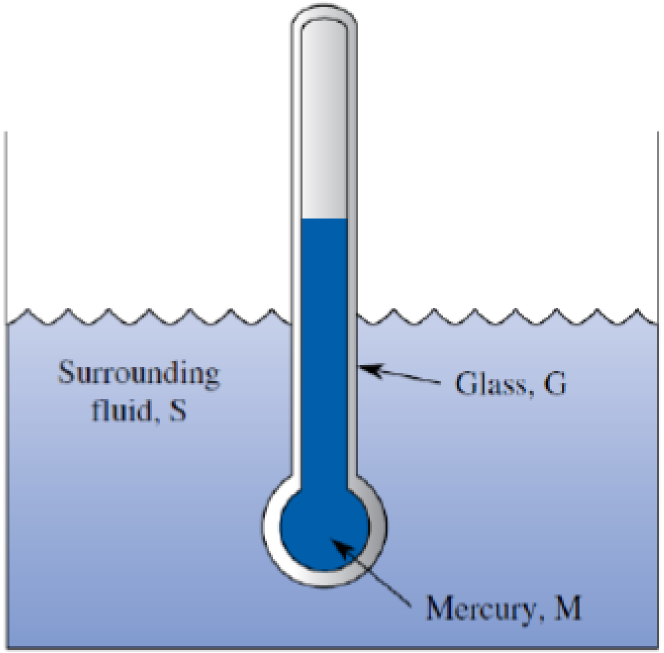
$T_M = T_S$

Illustration of Zeroth Law of Thermodynamics as basis for Temperature Measurement

Consider the mercury in glass thermometer shown.

The Zeroth Law tell us that if the glass is at the same temperature (thermal equilibrium) as the surrounding fluid, and if the mercury is at the same temperature as the glass, then the mercury is at the same temperature as the surrounding fluid.

Thus, the thermometer can be calibrated to show the temperature of mercury, and this temperature, by the Zeroth Law, is equal to the temperature of the surrounding fluid.



Zeroth law;
$T_G = T_S$
and
$T_M = T_G$
therefore,
$T_M = T_S$

The zeroth law of thermodynamics forms the basis for temperature measurement.

Temperature measurement is accomplished by the following:

1. Reference System & Reference Property
2. Reference Points
3. Formation of Temperature Scale

1. Reference System and Reference Property:

It is referred to as the thermometer and possesses a property that is measurable and changes with temperature.

The property that changes is referred to as a thermometric property.

The variation in the value of the thermometric property is taken as the measure of the variation of temperature.

Temperature Measurement

Some of the common thermometers with their thermometric properties are listed below:

Sl. No.	Thermometer	Thermometric property
1.	Mercury column in glass capillary	Volume (Length)
2.	Constant volume of gas enclosed in the vessel	Pressure
3.	Thermocouple	e.m.f.
4.	Electric resistance thermometer	Electric resistance
5.	Radiation thermometer	Radiation

Temperature – Reference Points

2. Reference points:

They are distinct, reproducible states at any place on the earth.

E.g.: Ice Point: A mixture of ice and water in thermal equilibrium at a pressure of 101.325 kPa. In the Celsius scale of temperature measurement, the temperature of this mixture is assigned the value 0 and written as 0°C.

Steam Point: It is the temperature of a mixture of water and wet steam in thermal equilibrium at a pressure of 101.325 kPa. In the Celsius scale, this temperature is assigned the value 100°C.

Besides these points, the other notable reference points are Gold Point (1063°C), Silver Point (960.8°C), Sulphur Point (444.6°C), Oxygen Point (-182.97°C).

Method before 1954

Till 1954, two reference points were used for temperature measurement:-

1. Ice Point
2. Steam Point

However, the use of the two fixed points was abandoned later due to the following reasons:-

a. The difficulty of achieving equilibrium between pure ice and air-saturated water, as when ice melts, it surrounds itself only with pure water and prevents intimate contact with air-saturated water
b. Extreme sensitiveness of steam point to change in pressure

Method after 1954

After 1954, the triple point of water, the state at which ice, liquid water and water vapour co-exist in thermal equilibrium, is the standard fixed point of thermometry.

This is because triple point of water is an easily reproducible state.

The temperature corresponding to triple point of water is 0.01^0C or 273.16 K.

Temperature – Reference Points

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Method after 1954

If T is temperature and X is the thermometric property we may write: -

$$T = AX$$

At triple point we may write $273.16 = AX_{\text{triple point}}$

$$A = \frac{273.16}{X_{\text{triple point}}}$$

Substituting for A we may write

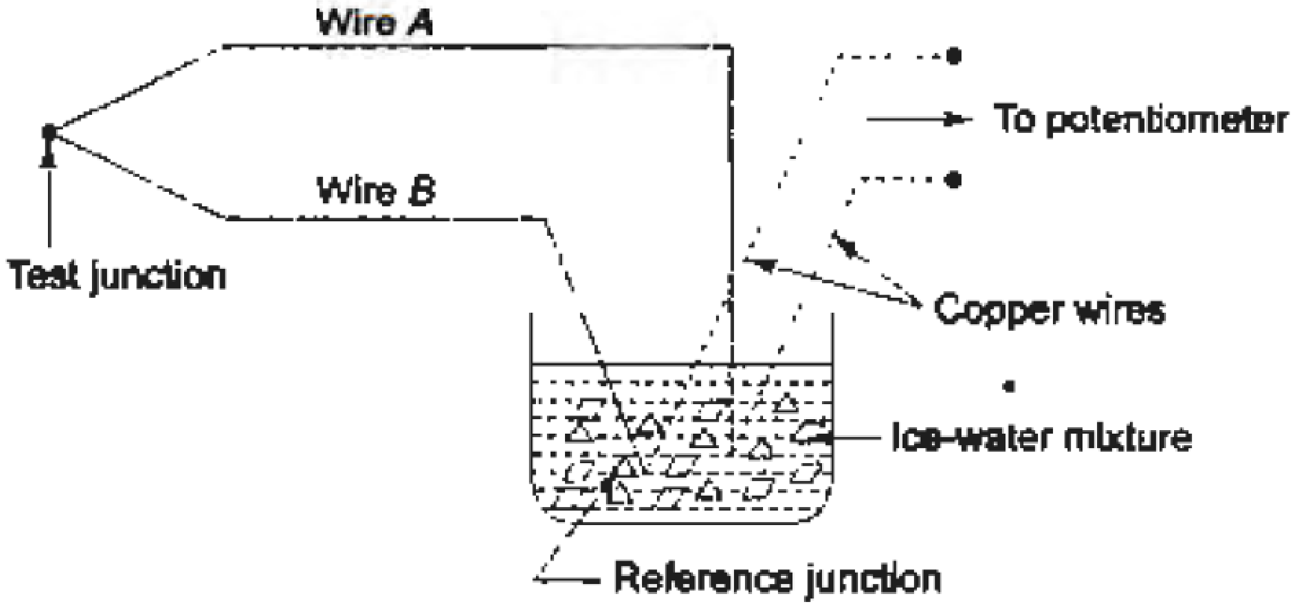
$$T = \left(\frac{273.16}{X_{\text{triple point}}}\right)X$$

$$T = 273.16\left(\frac{X}{X_{\text{triple point}}}\right)$$

The e.m.f. in a thermocouple with the test junction at t^0C on a gas thermometer scale and reference junction at ice point is given by

$$e = 0.25t - 6 \times 10^{-4}t^2, mV$$

The millivoltmeter is calibrated at ice and steam points. What will this thermometer read in a place where the gas thermometer reads 60^0C?



Solution

$$e_{ice} = 0.25(0) - 6 \times 10^{-4}(0^2) = 0$$

$$e_{steam} = 0.25(100) - 6 \times 10^{-4}(100^2) = 19 \text{ mV}$$

Since it is calibrated at ice and steam points, it is assumed that emf 'e' is a linear function of temperature between them.

$e = a + bt'$, where t' is the temperature on the linear scale.

At ice point

$0 = a + b(0) \rightarrow$ **a = 0**

At steam point

$19 = a + b(100) \rightarrow$ **b = 0.19**

$$\mathbf{e = 0.19t'}$$

Solution

When t = 50^{0}C, the emf generated is given by

$$e = 0.25(50) - 6 \times 10^{-4}(50^2) = 11 \text{ mV}$$

Substituting for e = 11mV, in the equation $e = 0.19t'$

$$11 = 0.19t'$$

$$t' = \frac{11}{0.19}$$

$$\mathbf{t' = 57.89\,^0C}$$

Thus we notice that the assumption of linear scale leads to an erroneous value of temperature.

% Error = $\left(\dfrac{57.89 - 50}{50}\right) \times 100 = 15.78\,\%$

A thermocouple with test junction at t°C on gas thermometer scale and reference junction at ice point gives the e.m.f. as

$$e = 0.20\,t - 5 \times 10^{-4}\,t^2 \text{ mV.}$$

The millivoltmeter is calibrated at ice and steam points. What will be the reading on this thermometer where the gas thermometer reads 70°C ?

$e = 0.20\,t - 5 \times 10^{-4} t^2$ mV

At ice point : When $t = 0°C$, $e = 0$

At steam point : When $t = 100°C$, $e = 0.20 \times 100 - 5 \times 10^{-4} \times (100)^2 = 15$ mV

Now, when $t = 70°C$ $e = 0.20 \times 70 - 5 \times 10^{-4} \times (70)^2 = 11.55$ mV

When the gas thermometer reads 70°C the thermocouple will read

$$t = \frac{100\ X\ 11.55}{15} = 77°C$$

The temperature t on a thermometric scale is defined in terms of a property K by the relation $t = a \ln K + b$, where a and b are constants.

The values of K are found to be 1.83 and 6.78 at the ice point and steam point, the temperatures of which are assigned the numbers 0 and 100 respectively.

Determine the temperature corresponding to a reading of K equal to 2.42 on the thermometer.

Solution

At ice point, $t = 0$ & $K = 1.83$

$t = a \ln K + b$ gives us $\rightarrow 0 = a \ln(1.83) + b \rightarrow 0 = a(0.6043) + b$

$\mathbf{b = -0.6043a}$

At steam point, $t = 100$, $K = 6.78$

$100 = a \ln(6.78) + b \rightarrow 100 = a(1.9139) - 0.6043a$

$\mathbf{a = 75.35}$

$b = -0.6043a \rightarrow b = -0.6043 \times 75.36 \rightarrow \mathbf{b = -45.53}$

When $K = 2.42$, $t = 75.36(\ln 2.42) - 45.53$.

$\mathbf{t = 21.3°C}$

A new scale N of temperature is divided in such a way that the freezing point of ice is 100°N and boiling point is 400°N. What is the temperature reading on this new scale when the temperature is 45°C? At what temperature will the Celsius and this new scale produce the same reading?

Solution

Assuming a linear relationship for N and a thermometric property X we write

$N = AX + B$

For ice point $\rightarrow N = AX + B \rightarrow 100 = AX_{ice} + B \rightarrow \mathbf{B = 100 - AX_{ice}}$

For steam point $\rightarrow N = AX + B \rightarrow 400 = AX_{steam} + B$

$\rightarrow 400 = AX_{steam} + (100 - AX_{ice})$

$$\rightarrow A = \frac{300}{X_{steam} - X_{ice}}$$

$$\rightarrow B = 100 - \frac{300X_{ice}}{X_{steam} - X_{ice}}$$

Solution

Substituting for A and B and simplifying we get

$$N = 300\left[\frac{X - X_{ice}}{X_{steam} - X_{ice}}\right] + 100$$

On similar lines for the Celsius Scale we get

$$C = 100\left[\frac{X - X_{ice}}{X_{steam} - X_{ice}}\right]$$

Substituting for C in the expression for N we may write

$$\mathbf{N = 3C + 100}$$

Solution

$$\mathbf{N = 3C + 100}$$

$$\text{For } C = 45°C$$

$$N = 3 \times 45 + 100$$

$$\mathbf{N = 235°N}$$

Both will read the same value when N = C

$$\text{i.e.,} N = 3C + 100 \rightarrow N = 3N + 100 \rightarrow 2N = -100$$

$$\mathbf{N = C = -50}$$

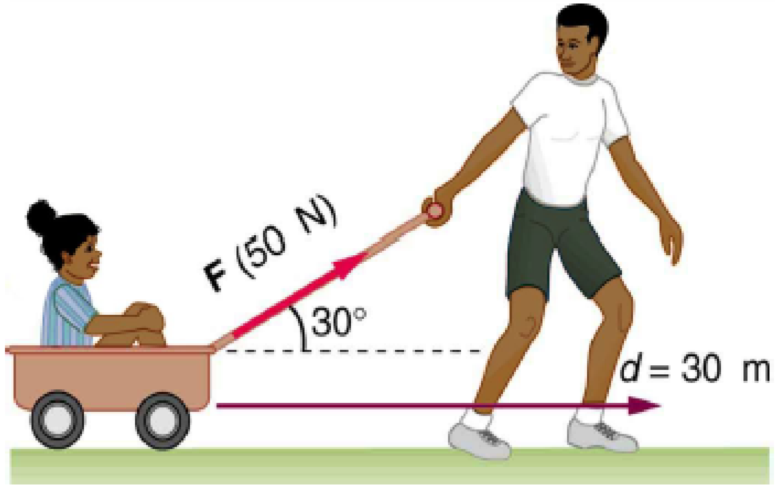
A platinum wire is used as a resistance thermometer. The wire resistance was found to be 10 ohm and 16 ohm at ice point and steam point respectively, and 30 ohm at Sulphur point of 444.6°C.

Find the resistance of the wire at 300°C, if the resistance varies with temperature by the relation $R = R_o(1 + \alpha t + \beta t^2)$

Work

From engineering mechanics point of view, work is said to be done when the point of application of a force moves through a certain distance.

The amount of work done is evaluated as the product of the force applied and the distance moved.



$$W = \text{Force} \times \text{distance}$$
$$= 50 \cos 30^0 \times 30$$
$$= 1299.04\ \text{N}$$

Work

But from thermodynamics point of view, work is treated as a form of energy in transition, which is observed as it crosses the system boundary.

In the language of thermodynamics, work is defined as follows: -

"Work is said to be done by a system, if the sole effect, external to the system, can be reduced to the raising of a weight".

We note that in the definition of work, it is not mentioned that weight is raised every time work is done by a system.

It only states that the sole effect external to the system can be reduced to the raising of a weight.

Illustration of Work

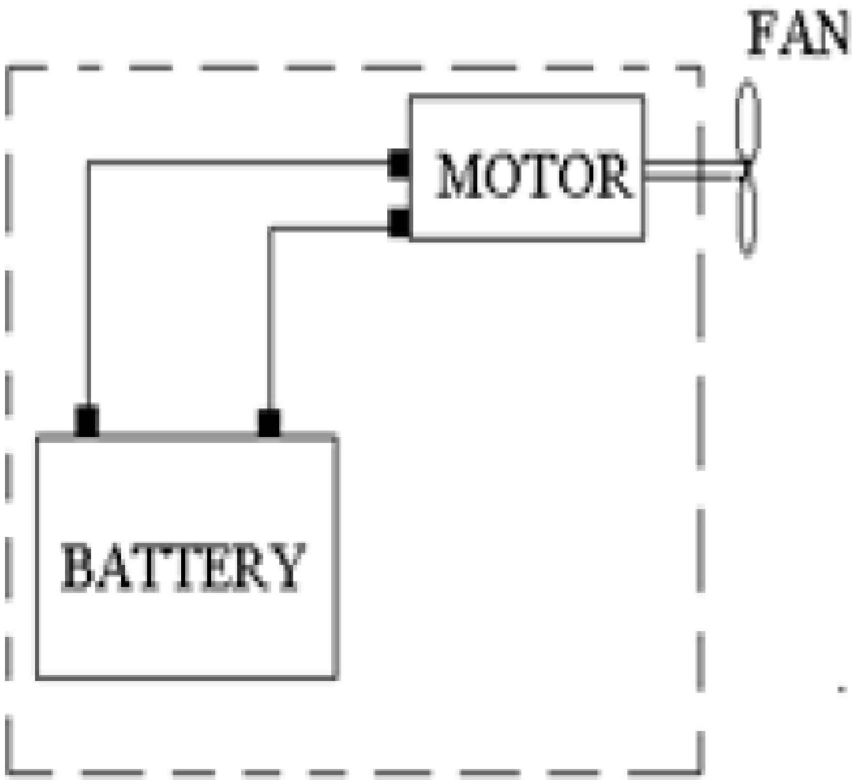


Illustration of Work

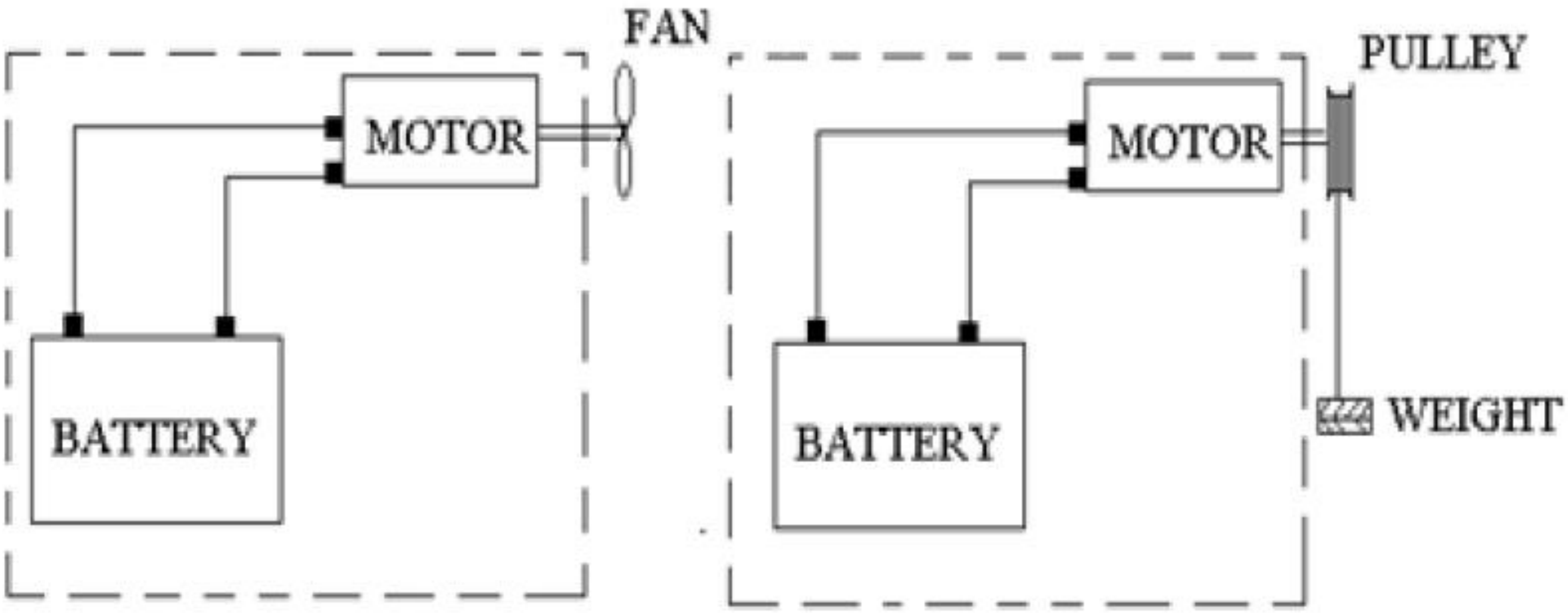
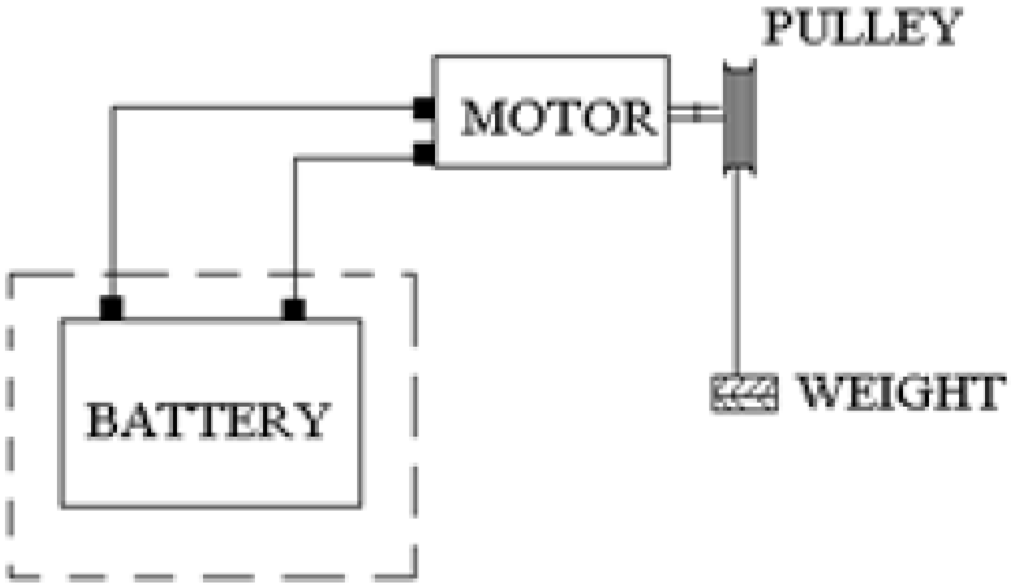


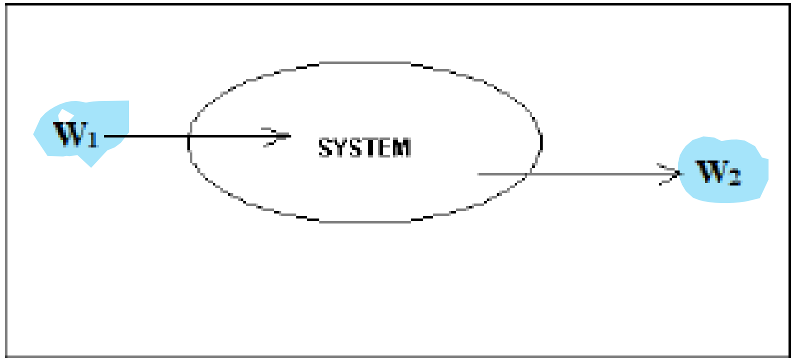
Illustration of Work



Sign Conventions of Work

Work done by the system is treated positive

Work done on the system is treated negative.

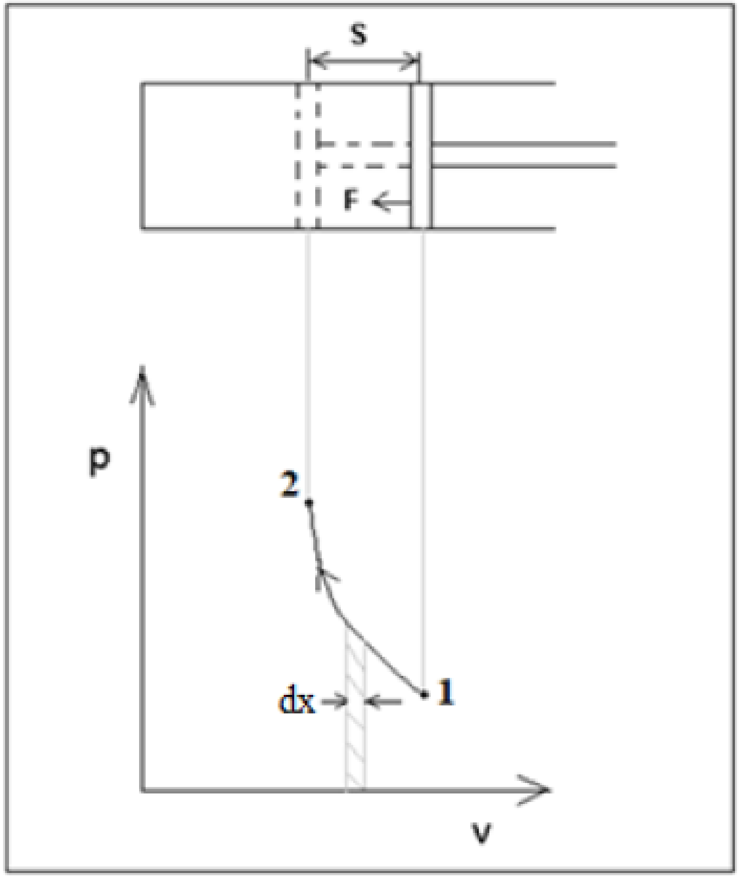


W_1 is -ve and W_2 is +ve

Units of work → joules(J), kilo joules(kJ)

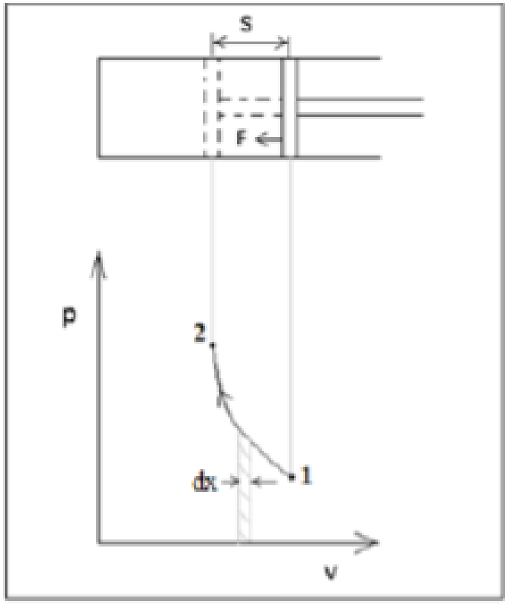
Sometimes work transferred/unit time is mentioned and the unit would be J/s or Watts (W).

Moving boundary or pdV work



Consider a fixed quantity of gas enclosed in a cylinder provided with a piston, as shown. Let the gas enclosed be treated as the system. Let it be compressed from initial state 1 to final state 2 by means of a quasi-static process.

Moving boundary or pdV work



Let F be the force applied and A be the cross sectional area of the piston. Let p be the pressure exerted on the gas.
Between the end states 1 and 2, consider a small displacement dx as indicated.
Let ∂W be the work done to achieve this small displacement.

Moving boundary or pdV work

We may write

$$\partial W = F \times dx$$

$$\partial W = (p \times A) \times dx$$

$$\partial W = p \times (A \times dx)$$

$$\partial W = p \times dV$$

To get the total work done between 1 and 2, we need to integrate: -

$$\int_1^2 \partial W = \int_1^2 p\, dV$$

$$W_{1-2} = \int_1^2 p\, dV$$

Moving boundary or pdV work

The expression $\int pdV$ can be integrated only if we know the relation between p and V.

When the relation between p and V is defined, the path followed gets defined. The path depends on the type of process.

Or, we can say that for different processes there are different paths.

Moving boundary or pdV work for Isothermal Process

For an Isothermal Process

We have $P_1V_1 = P_2V_2 = PV = \text{Constant}$

Hence $P = \text{Constant}/V$

$$\text{Moving Boundary Work, } W = \int_1^2 P dV$$

$$= \int_1^2 \left(\frac{\text{Constant}}{V}\right) dV$$

$$= \text{Constant} \int_1^2 \left(\frac{dV}{V}\right)$$

$$= \text{Constant} \ln(V)_1^2$$

$$= P_1V_1 \ln\left(\frac{V_2}{V_1}\right)$$

Moving boundary or pdV work for Various processes

Sl. No	Process	Relation between P and V	Expression for pdV work
1	Isothermal process	PV = const. $P_1V_1 = P_2V_2$	$W = P_1V_1 \ln\left(\frac{V_2}{V_1}\right)$
2	Adiabatic process	PV^γ = constant $P_1V_1^\gamma = P_2V_2^\gamma$	$W = \frac{p_1V_1 - p_2V_2}{\gamma - 1}$
3	Polytropic process	PV^n = const $P_1V_1^n = P_2V_2^n$	$W = \frac{p_1V_1 - p_2V_2}{n - 1}$
4	Isochoric process	V =constant. dV = O $P_1/P_2 = T_1/T_2$ (Kelvin)	W = O
5	Isobaric process	P = constant. dP = O $V_1/T_1 = V_2/T_2$	$W = P (V_2 – V_1)$

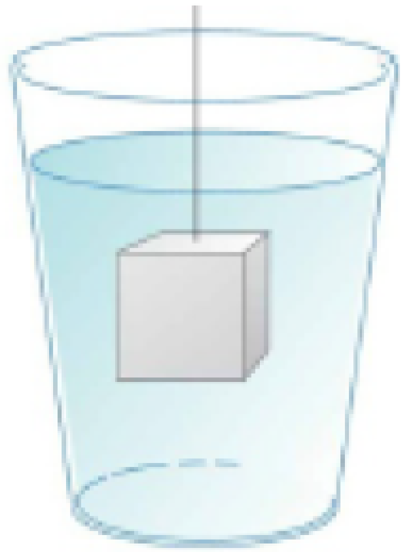
Other forms of Work

Sl. No	Type of Work Transfer	Expression for work
1	Shaft Work	• $W = \text{Torque} \times \text{Angular Displacement}$ $W = T \times 2\pi$, Joules per rotation • $W = T \times 2\pi \times n$, Joules for n rotations • Work done per second $=$ $\dot{W} = \frac{T \times 2\pi N}{60}$, Joules per second, where N = number of rotations per minute (rpm)

Other forms of Work

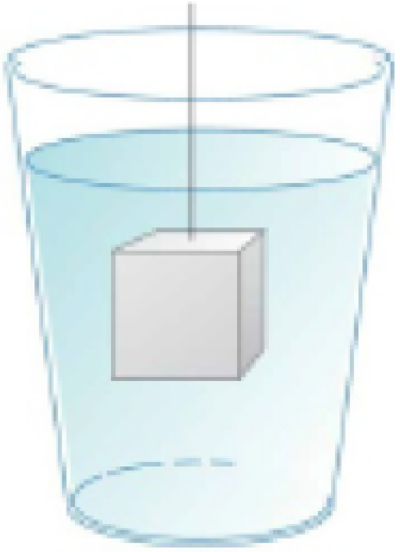
Sl. No	Type of Work Transfer	Expression for work
2	Electric Work	W = Voltage * Current
3	Surface Tension Work	W = Surface Tension * Area = σ*A
4	Work done in stretching a wire	$W = -\frac{AEL}{2}(\varepsilon_2^2 - \epsilon_1^2)$ where A = cross sectional area E = Young's Modulus L = Length of the specimen ε = Linear Strain
5	Flow Work	W= pressure*volume

HEAT is defined as a form of energy in transition taking place due to a difference in temperature.



Consider a hot copper block and a beaker of cold water.
Let the hot block be immersed in cold-water.
On immersion, we note that there is a transfer of energy from the block to the cold water.
The transfer of energy is happening due to a difference in temperature between the block and the water.
This form of energy transfer is referred to as heat or heat transfer.

Heat



Heat is transferred only till there is a temperature difference.

Once equality of temperature has been attained, there is no heat or heat transfer.

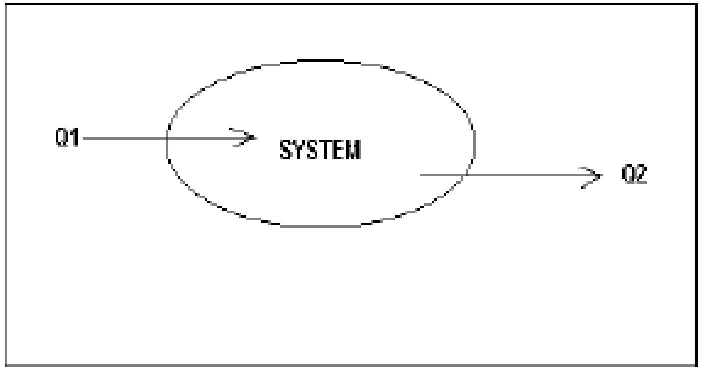
From this we conclude that systems do not possess heat, they only possess energy.

Heat is a transient phenomena, which can be observed at the system boundary.

Sign Convention for Heat

Heat added to a system is treated +ve

Heat removed from a system is treated as –ve.



Q1 is +ve

Q2 is –ve

Units of heat → joules(J), kilo joules(kJ)

Sometimes heat transferred/unit time is mentioned and the unit would be J/s or Watts(W).

Comparison between Work and Heat

Systems do not possess heat or work, they only possess energy.

Transient phenomena: Heat and Work are observed only there is transfer of energy and hence are transient in nature.

Boundary phenomena: Both heat and work are observed at the system boundary. On change of the system boundary the form of energy transfer may change from heat to work or vice versa.

Path functions: Both heat and work are path functions and hence inexact differentials.

Comparison between Work and Heat – Sign Convention

Heat:

Heat added to the system is +ve

Heat removed from the system is –ve.

Work:

Work done by the system is +ve

Work done on the system is –ve

A mass of 1.5 kg of air is compressed in a quasi-static process from 0.1 MPa to 0.7 MPa during which PV=constant. If the initial density of air is 1.16 kg/ m³, determine the work done by the system.

Important Observations

Process is isothermal since PV=constant

$$p_1V_1 = p_2V_2 \text{ OR } \frac{p_1}{p_2} = \frac{V_2}{V_1}$$

$$v = \frac{V}{m}$$

Data provided

$$m = 1.5\ \text{kg};\ p_1 = 0.1\ \text{MPa};$$

$$p_2 = 0.7\ \text{MPa};\ \rho_1 = 1.16\frac{kg}{m^3}$$

Solution

$$W_{1-2} = p_1V_1\ln\frac{V_2}{V_1} = p_1V_1\ln\frac{\mathbf{p_1}}{\mathbf{p_2}}$$

$$= p_1(\mathbf{mv_1})\ln\frac{p_1}{p_2} = m \times p_1\ v_1 \times \ln\frac{p_1}{p_2}$$

$$W_{1-2} = 1.5 \times 0.1 \times \left(\frac{1}{1.16}\right)\ln\frac{0.1}{0.7}$$

$$\mathbf{W_{1-2} = -0.2516\ MJ}$$

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A mass of gas is compressed in a quasi static process from 80 kPa, 0.1m³ to 0.4MPa , 0.03m³. Assuming the P & V are related by up PVⁿ = constant, determine the work done by the system.

Important Observations

Process is polytropic → PV^n = constant

Data provided

$p_1 = 80\text{ kPa};\ V_1 = 0.1\ m^3$

$p_2 = 0.4\text{ MPa};\ V_2 = 0.03\ m^3$

Solution

1. Determination of polytropic index n

$$p_1V_1^n = p_2V_2^n$$

$$\left(\frac{p_1}{p_2}\right) = \left(\frac{V_2}{V_1}\right)^n$$

Taking log on both sides

$$\mathrm{Log}\left(\frac{p_1}{p_2}\right) = n \times \mathrm{Log}\left(\frac{V_2}{V_1}\right)$$

$$\mathrm{Log}\left(\frac{80}{400}\right) = n \times \mathrm{Log}\left(\frac{0.03}{0.1}\right)$$

Solving we get **n = 1.337**

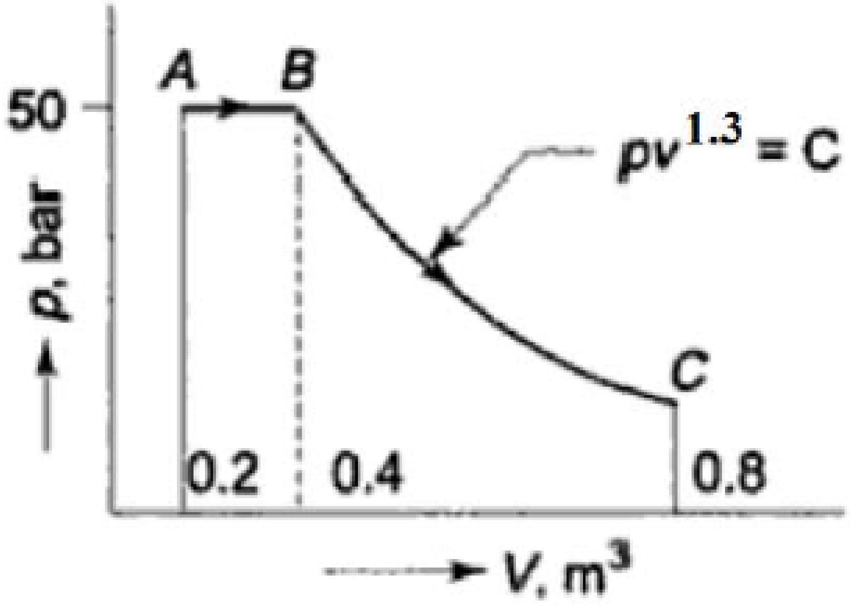
2. Determination of work done

$$W_{1-2} = \frac{p_1V_1 - p_2V_2}{n-1} \text{ for a polytropic process}$$

$$W_{1-2} = \frac{(80 \times 0.1) - (400 \times 0.03)}{1.337 - 1}$$

$$\mathbf{W_{1-2} = -11.87\ kJ}$$

Determine the total work done by a gas system following an expansion process shown in the figure.



Important Observations

A-B: Constant Pressure Process

B-C: Polytropic Process

Data Provided

$p_A = p_B = 50 \text{ bar}$

1 bar = 100 kPa

$V_A = 0.2 \text{ m}^3; V_B = 0.4 \text{ m}^3; V_C = 0.8 \text{m}^3$

$p_B {V_B}^{1.3} = p_C {V_C}^{1.3}$

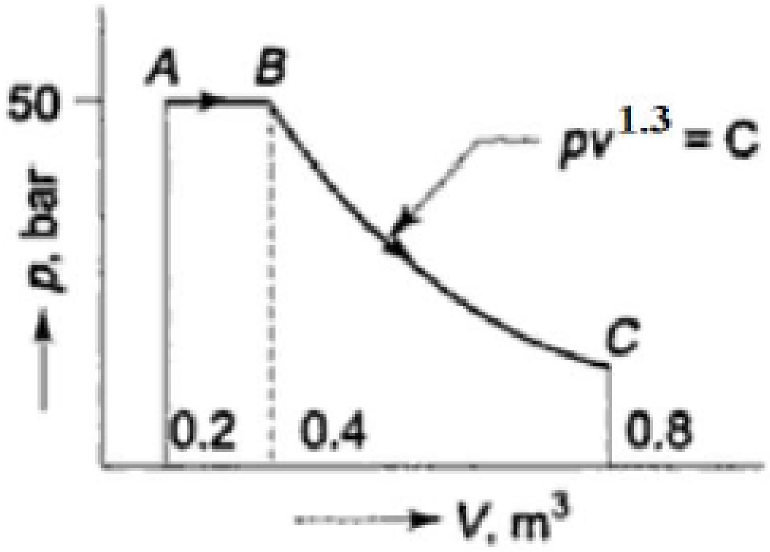
Solution

1. Determination of p_C

$$p_B V_B^{1.3} = p_C V_C^{1.3}$$

$$p_C = p_B \left(\frac{V_B}{V_C}\right)^{1.3} = 50 \times 100 \times \left(\frac{0.4}{0.8}\right)^{1.3}$$

$$\mathbf{p_C = 2030.63\ kPa}$$



Solution (Cont'd)

2. Determination of total work done

$$W_{A-B} = p_A(V_B - V_A) = 50 \times 100 \times (0.4 - 0.2)$$

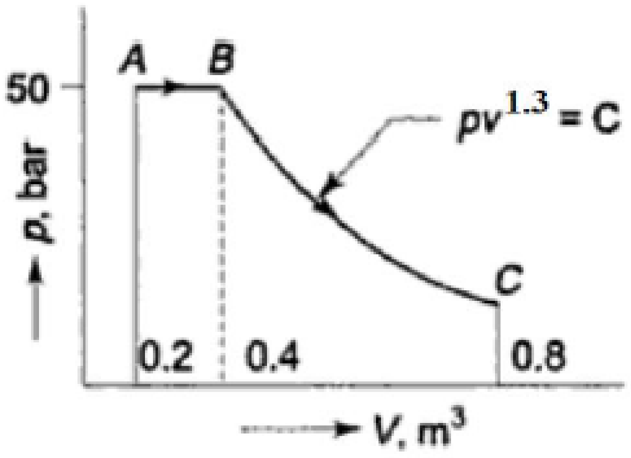
$$\mathbf{W_{A-B} = 1000\ kJ}$$

$$W_{B-C} = \frac{p_B V_B - p_C V_C}{n-1} = \frac{50 \times 100 \times 0.4 - 2030.63 \times 0.8}{1.3 - 1}$$

$$\mathbf{W_{B-C} = 1251.65\ kJ}$$

$$W_{Total} = W_{A-B} + W_{B-C} = \mathbf{1000 + 1251.65}$$

$$\mathbf{W_{Total} = 2251.65\ kJ}$$



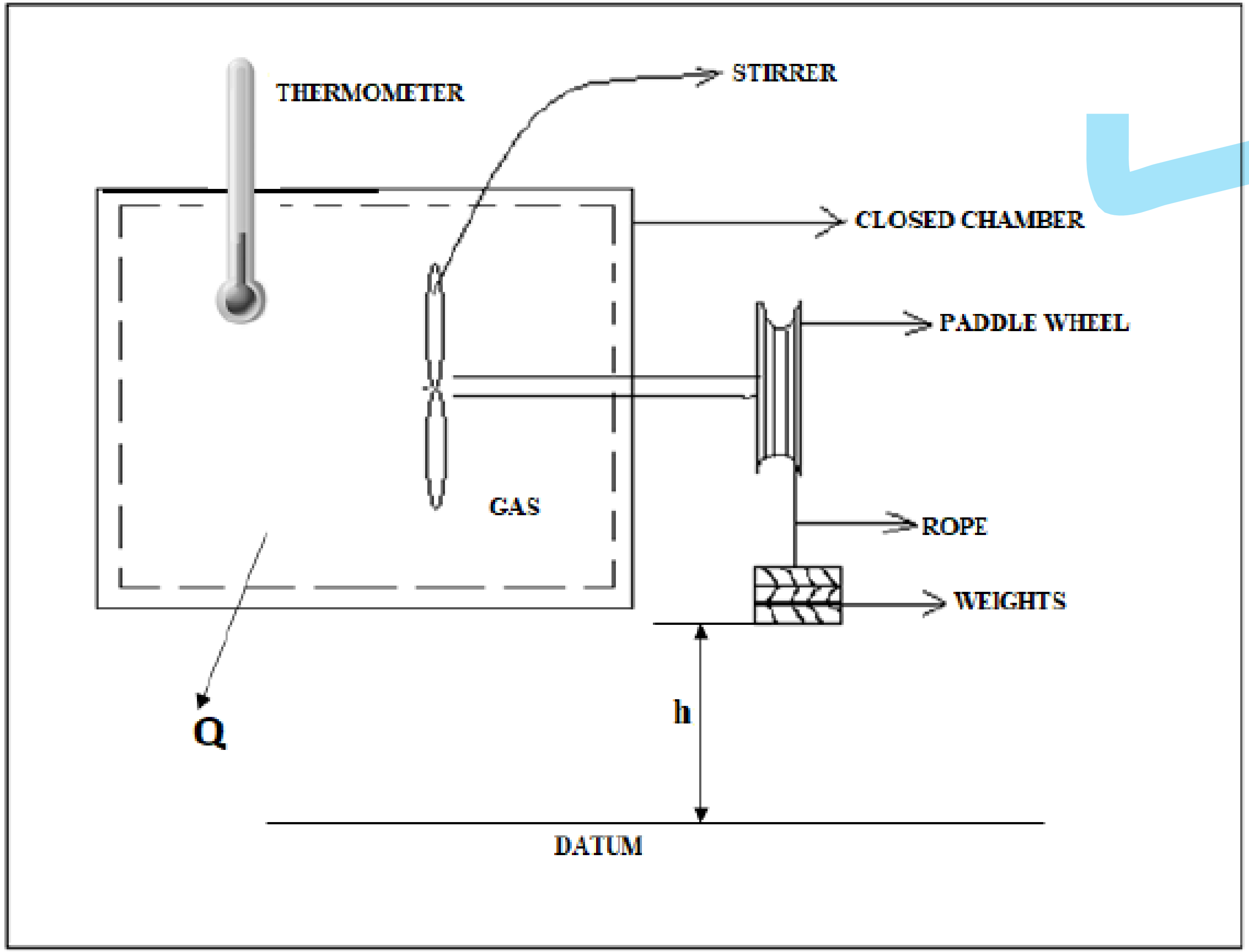
First Law of Thermodynamics – Joule's Experiment

In 1845, Joule published a paper entitled "**The Mechanical Equivalent of Heat**", in which he specified a numerical value for the amount of mechanical work required to produce a unit of heat.

In particular Joule had experimented on the amount of mechanical work generated by friction needed to raise the temperature of a pound of water by one degree Fahrenheit and found a consistent value of 778.24 foot pound force (4.1550 $J.cal^{-1}$ later corrected to 4.1868 $J.cal^{-1}$)

Joule contended that motion and heat were mutually interchangeable and that, in every case, a given amount of work would generate the same amount of heat.

First Law of Thermodynamics – Joule's Experiment



First Law of Thermodynamics – Joule's Experiment

Energy imparted to paddle wheel and converted to work done on gas by stirrer = W = $m_w gh$

where m_w is the mass of the weights and h is the height of fall.

The temperature of the gas rises due to the conversion of work to heat by friction. Let this be ΔT.

We have Q = $mc\Delta T$, where m is the mass of the gas and c the specific heat.

It is observed that W α Q for every different height of fall.

On removing this amount of heat the system is restored to its initial state, thus completing a cycle.

This was the Joule's experiment.

Statement of First Law of Thermodynamics for Cyclic Process

‘*When a system undergoes a cyclic process, the algebraic sum (or cyclic integral), of heat transfers is proportional to, the algebraic sum (or cyclic integral), of work transfers.*’

Or we say

$$\sum_{\text{cycle}} W \;\alpha\; \sum_{\text{cycle}} Q$$

$$\Sigma_{\text{cycle}} W = J\,\Sigma_{\text{cycle}} Q,$$

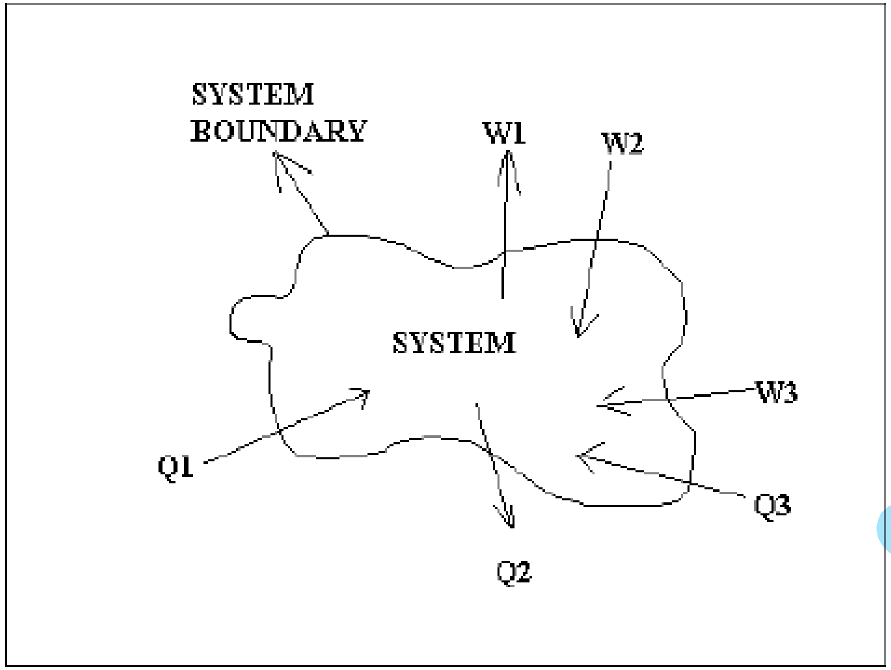
where J is the proportionality constant called the Joule’s constant.

In the language of calculus

$$\oint \partial W = J \oint \partial Q$$

J = 418.68 kJ/kCal OR
J = 427 kgf-m/ kCal

Statement of First Law of Thermodynamics for Cyclic Process



Consider the system shown.

Let it experience the heat and work transfers indicated while undergoing a cyclic process.

By law of conservation of energy

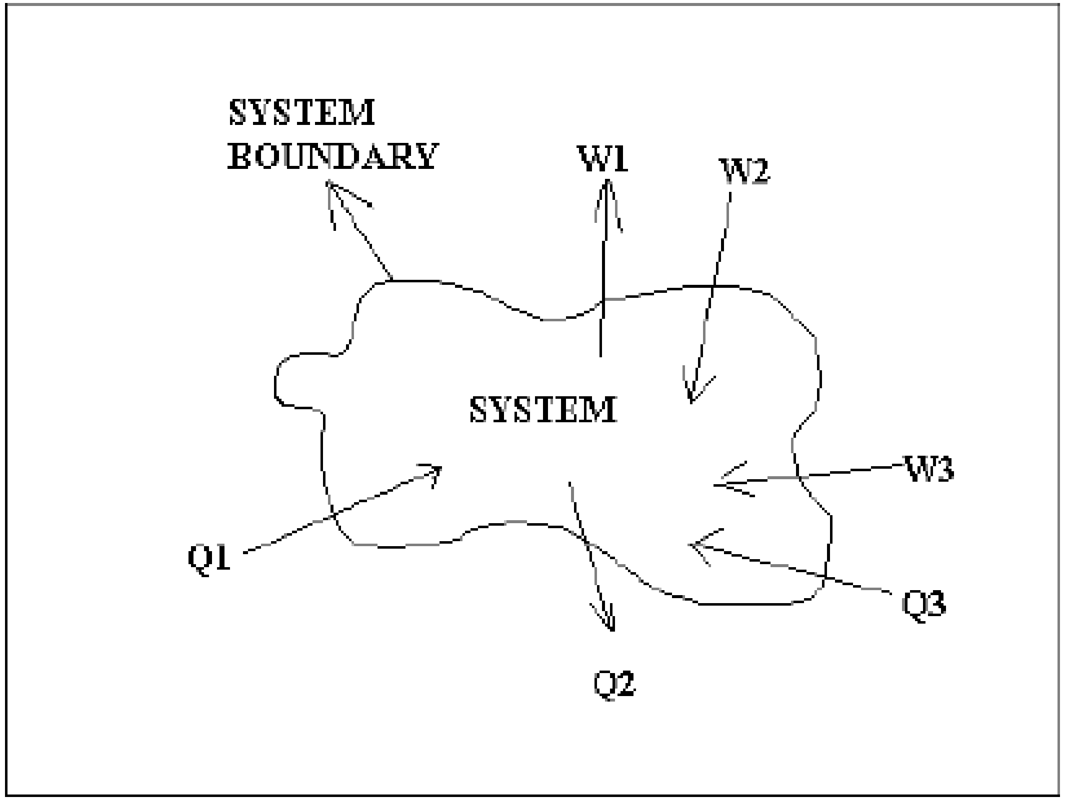
Total energy entering the system = Total energy leaving the system

$Q_1+Q_3+W_2+W_3=Q_2+W_1$

Putting the Qs on side and Ws on the other side we have

$W_1-W_2-W_3 = Q_1-Q_2+Q_3$

Statement of First Law of Thermodynamics for Cyclic Process



Or we say

$$\sum_{\text{cycle}} W = \sum_{\text{cycle}} Q$$

This is itself the statement of the First Law of Thermodynamics for a closed system undergoing a cyclic process

First Law of Thermodynamics for a closed system undergoing process

It can be shown that the quantity $(\partial Q - \partial W)$ is a property of the system and we call this property ENERGY with symbol E

OR $(\partial \mathbf{Q} - \partial \mathbf{W}) = \mathbf{dE}$

$$\left.\begin{aligned} \partial Q - \partial W &= dE \\ \partial Q &= dE + \partial W \end{aligned}\right\} \quad \textbf{(4)}$$

Equations (4) are the differential forms of the first law for a closed system undergoing an infinitesimal change of state.

Between end states 1 and 2 we can integrate and write

$$\int_1^2 \partial Q = \int_1^2 dE + \int_1^2 \partial W$$

First Law of Thermodynamics for a closed system undergoing process

$$\left.\begin{aligned}&\mathbf{Q_{1-2} = (E_2 - E_1) + W_{1-2}}\\ &\text{OR in general } \mathbf{Q = \Delta E + W}\\ &\text{OR } \mathbf{Q - W = \Delta E}\end{aligned}\right\} \quad (5)$$

Equations (5) represent the first law of thermodynamics for a closed system undergoing a finite change of state.

Energy or Stored Energy of a System

Energy of a System

- Potential Energy = mgz
- Internal Energy, U
- Kinetic Energy = $\frac{mV^2}{2}$
- Other Forms: Magnetic Energy, Electrical Energy, Distortion Energy, Surface Energy, etc

Internal Energy of a System

Internal energy is attributed to the energy inherent in the system inclusive of

a. Vibrational kinetic energy of the molecules.
b. Translatory and rotatory energy of the molecules
c. Energy needed to pack the molecules (molecular potential energy)
d. Binding energy present in the nucleus etc.

Internal energy is an extensive property while specific internal energy (energy per unit mass) is an intensive property.

Symbol for Internal Energy is 'U', with units J, kJ.. etc.

Symbol for specific internal energy is 'u' , with units J/kg, kJ/kg.. etc

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1. During one cycle, the working fluid of an engine engages in two work interactions : 15 kJ to the fluid and 44 kJ from the fluid, and three heat interactions, two of which are known : 75 kJ to the fluid and 40 kJ from the fluid. Evaluate the magnitude and direction of the third heat transfer.

Important Observations

Heat transferred to the fluid is taken with *a positive sign*, while that transferred *from* the fluid is with *a negative sign*.

Work transferred to the fluid is taken with a *negative sign*, while that transferred *from* the fluid is with *a positive sign*.

Solution

$$\sum_{\text{cycle}} Q = \sum_{\text{cycle}} W$$

$$+75 - 40 + Q = 44 - 15$$

Q = -6 kJ.

2. A closed system passes through a complete cycle of 4 processes. The sum of all heat transfers is –170 kJ/cycle. The system completes 100 cycles/min. Complete the following table showing the method for each item and compute the net rate of work output in kW.

PROCESS	Q (kJ/min)	W (kJ/min)	ΔE (kJ/min)
a –b	0	2,170	
b–c	–21,000	0	
c–d	–2,100		–36,600
d–a			

Important Observations

The values of heat, work and energy change are given in kJ/min. The sum of all heat transfers is mentioned in kJ/cycle.

Data Provided

$$\sum_{\text{cycle}} Q = -170\,\frac{\text{kJ}}{\text{cycle}}$$

Number of cycles per minute = 100

PROCESS	Q (kJ/min)	W (kJ/min)	ΔE (kJ/min)
a –b	0	2,170	-2,170
b–c	–21,000	0	-21,000
c–d	–2,100	34,500	-36,600
d–a			59,770

Solution

Process a–b

$Q_{a-b} = W_{a-b} + \Delta E_{a-b}$

$0 = 2,170 + \Delta E_{a-b}$

$\Delta E_{a-b} = -2,170$ kJ/min

Process b–c

$Q_{b-c} = W_{b-c} + \Delta E_{b-c}$

$-21,000 = 0 + \Delta E_{b-c}$

$\Delta E_{b-c} = -21,000$ kJ/min

Process c–d

$Q_{c-d} = W_{c-d} + \Delta E_{c-d}$

$-2100 = W_{c-d} - 36,600$

$W_{c-d} = 34,500$ kJ/min

$\Sigma \Delta E = 0$

$\Delta E_{a-b} + \Delta E_{b-c} + \Delta E_{c-d} + \Delta E_{d-a} = 0$

$-2,170 - 21,000 - 36,600 + \Delta E_{d-a} = 0$

$\Delta E_{d-a} = 59,770$ kJ/min

First Law of Thermodynamics - Numericals

$\Sigma Q = -170$ kJ / cycle

= -170 x 100 cycles / min = -17,000 kJ / min

$Q_{a-b} + Q_{b-c} + Q_{c-d} + Q_{d-a} = -17,000$

$0 - 21,000 - 2,100 + Q_{d-a} = -17,000$

Q_{d-a} **= 6,100 kJ / min**

PROCESS	Q (kJ/min)	W (kJ/min)	ΔE (kJ/min)
a –b	0	2,170	-2,170
b–c	–21,000	0	-21,000
c–d	–2,100	34,500	-36,600
d–a	6,100	-53,670	59,770

Process d–a

$Q_{d-a} = W_{d-a} + \Delta E_{d-a}$

$6,100 = W_{d-a} + 59,770$

$W_{d-a} = -53,670$ kJ/min

By First Law of thermodynamics $\Sigma Q = \Sigma W$ = -17,000 kJ/min

Therefore the **net work output** = –17,000 kJ/min = $\frac{-17,000}{60} = -283.33$ kW

3. 1.5 kg of liquid having constant specific heat of 2.5 kJ/kg K is stirred in a well insulated chamber, causing the temperature to rise by 15°C. Find ΔE and W for the process.

Important Observations

The temperature of the liquid rises in spite of no transfer of heat.
This is because of conversion of the stirring work to heat by friction.

Data Provided

Mass of the liquid = m = 1.5 kg

Specific Heat of the liquid = C = 2.5 kJ/kg-K

Temperature Rise = ΔT = 15 ^{0}C

Solution

$$\Delta E = mC\Delta T = 1.5 \times 2.5 \times 15$$

$$\mathbf{\Delta E = 56.25\ kJ}$$

$$Q = \Delta E + W$$

$$0 = \Delta E + W$$

$$W = -\Delta E$$

$$\mathbf{W = -56.25\ kJ}$$

First Law of Thermodynamics - Limitations

The First Law of Thermodynamics is another form of the Law of Conservation of Energy. It merely states that when a process takes place, energy can neither be created nor destroyed.

However, from many observations of common experiences, it is observed that

1. Processes follow a definite direction.
2. Heat and work are qualitatively different.

These are not addressed by the I Law of Thermodynamics and thus are referred to as 'Limitations of the I Law of Thermodynamics'.

Directional Nature of Processes

I - Processes Follow A Definite Direction

- ✓ Heat flows from a hot body to a cold body on its own but never vice-versa.
- ✓ Consider a vehicle moving up hill at the expense of fuel burnt. If we reverse this process i.e., make it move down hill, it is not possible to get the fuel back.
- ✓ Water flows from a higher to lower level and not vice-versa.

Directional Nature of Processes

I - Processes Follow A Definite Direction

- ✓ Electric current flows from higher to lower potential and not vice-versa.
- ✓ A magnetic pole would move from higher to lower potential and not vice-versa.

Even if these were to happen, it would still satisfy the 1st Law of Thermodynamics.

II - Heat and Work are Qualitatively Different

Heat and Work are qualitatively different. Heat is referred to as a qualitatively lower form of energy while work is qualitatively higher.

All work can be dissipated as heat while all heat cannot be converted to work by any device working in a thermodynamic cycle.

Even if this were to happen, it would still satisfy the 1st Law of Thermodynamics.

Important Definitions

Heat Reservoir: is a body of infinite heat capacity, whose temperature is not affected by any heat transfer.
It can also be defined as a body of infinite heat capacity, which can absorb or supply heat without any change in its temperature.

Heat Source : is a heat reservoir which can supply heat without any change in its temperature.

Heat Sink : is a heat reservoir which can absorb heat without any change in temperature.

Important Definitions - Source

The Sun

Important Definitions - Source

Furnace

Important Definitions - Sink

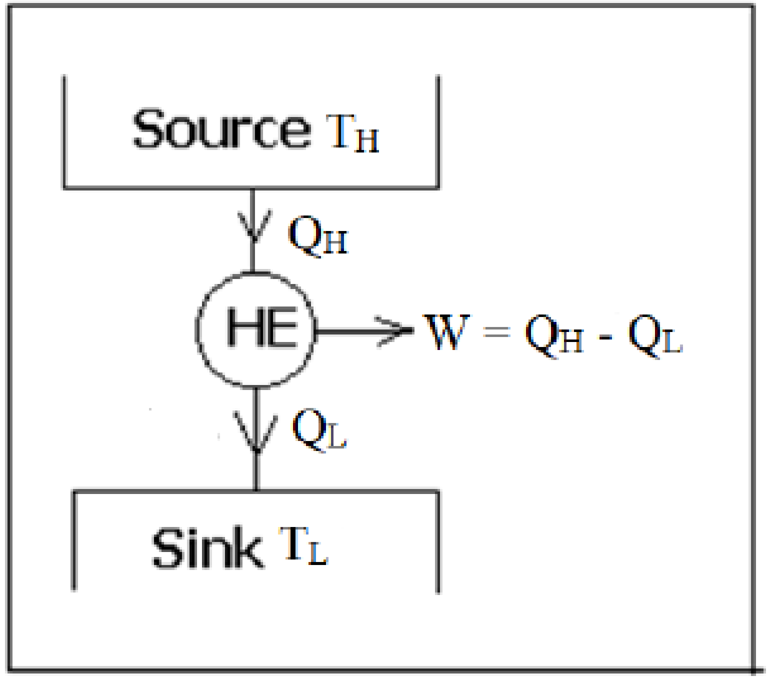
The Atmosphere

Important Definitions - Sink

The Ocean

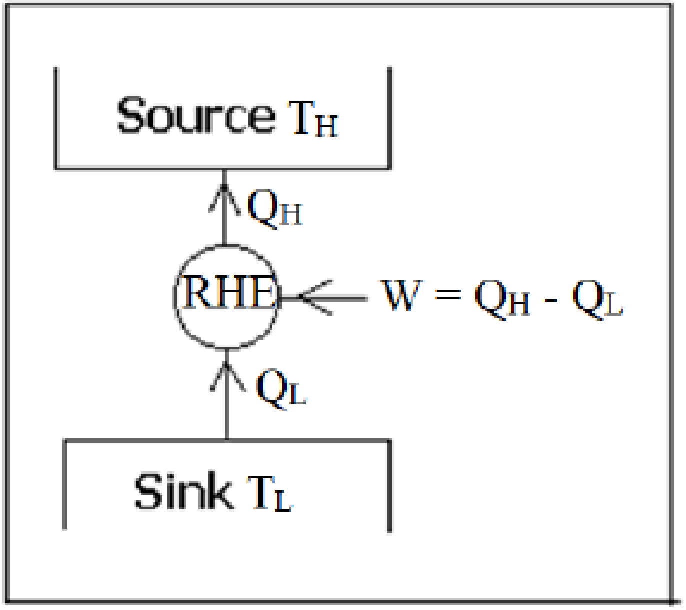
Important Definitions – Heat Engine

Heat Engine : is a device that works in a thermodynamic cycle and produces net positive work while absorbing heat from a source and dissipating heat to a sink.



Important Definitions – Reversed Heat Engine

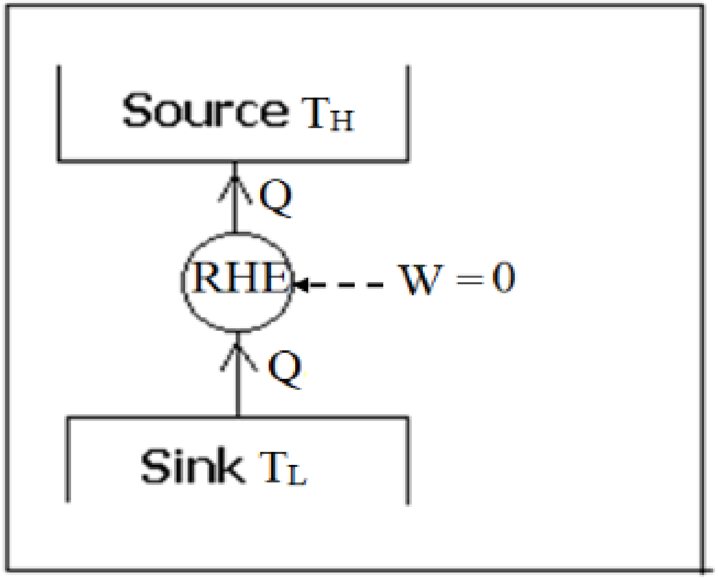
<u>Reversed Heat Engine</u>: is a device that operates in a thermodynamic cycle and transfers heat from a low temperature body (sink) to a high temperature body (source) with the aid of external work.



Statement of Second Law of Thermodynamics

Clausius Statement

It is impossible to construct a device that operates in a thermodynamic cycle and transfers heat from a cold body to a hot body without the input of external energy.



PRINCIPLE OF REFRIGERATION

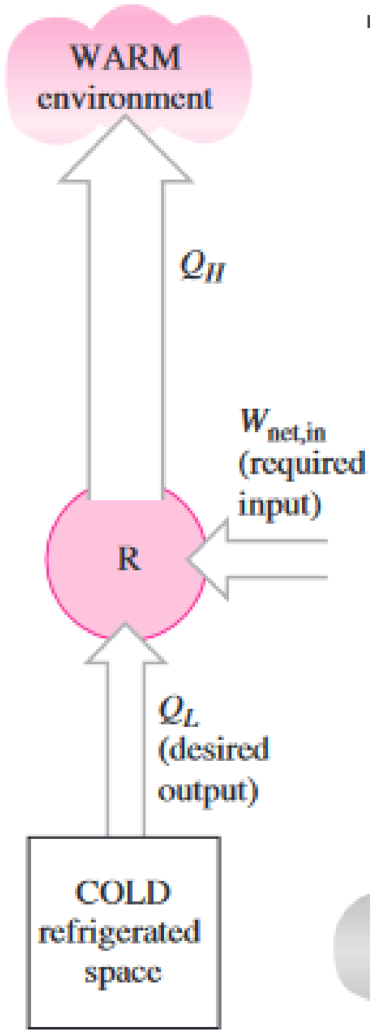
- ***The process of cooling or reducing the temperature of a substance below that of the surrounding atmosphere and maintaining this lower temperature within the boundary of a given space is called refrigeration.***
- The machine or device employed to produce refrigeration effect is called **refrigerator.**
- In order to keep the substance cold, heat must be continuously removed from the given substance.
- According to the law of thermodynamics, heat naturally flows from a hot substance to a cold substance. But if heat has to flow from a cold substance to a hot substance, some form of work has to be performed.

PRINCIPLE OF REFRIGERATION

- Refrigeration works on the principle that heat is continuously extracted from the low temperature substance ***by performing mechanical work***. This heat is then rejected to the surrounding atmosphere (high temperature level).

- A carrier substance is used to extract the heat and this substance is known as ***refrigerant***.

- The refrigerant is a chemical substance like ammonia, carbon di oxide, methyl chloride, Freon etc.



MECHANICAL ENERGY AND EFFICIENCY

- Many fluid systems are designed to transport a fluid from one location to another at a specified flow rate, velocity, and elevation difference, and the system may generate mechanical work in a turbine or it may consume mechanical work in a pump or fan during this process.

- These systems do not involve the conversion of nuclear, chemical, or thermal energy to mechanical energy. Also, they do not involve heat transfer in any significant amount, and they operate essentially at constant temperature.

- Such systems can be analyzed conveniently by considering only the mechanical forms of energy and the frictional effects that cause the mechanical energy to be lost (i.e., to be converted to thermal energy that usually cannot be used for any useful purpose)

- The **mechanical energy** is defined as the form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.

Mechanical energy is a useful concept for flows that do not involve significant heat transfer or energy conversion, such as the flow of gasoline from an underground tank into a car.

MECHANICAL ENERGY AND EFFICIENCY

- Kinetic and potential energies are the familiar forms of mechanical energy. Thermal energy is not mechanical energy, however, since it cannot be converted to work directly and completely (the second law of thermodynamics).

- The mechanical energy of a flowing fluid can be expressed on a unit-mass basis as

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

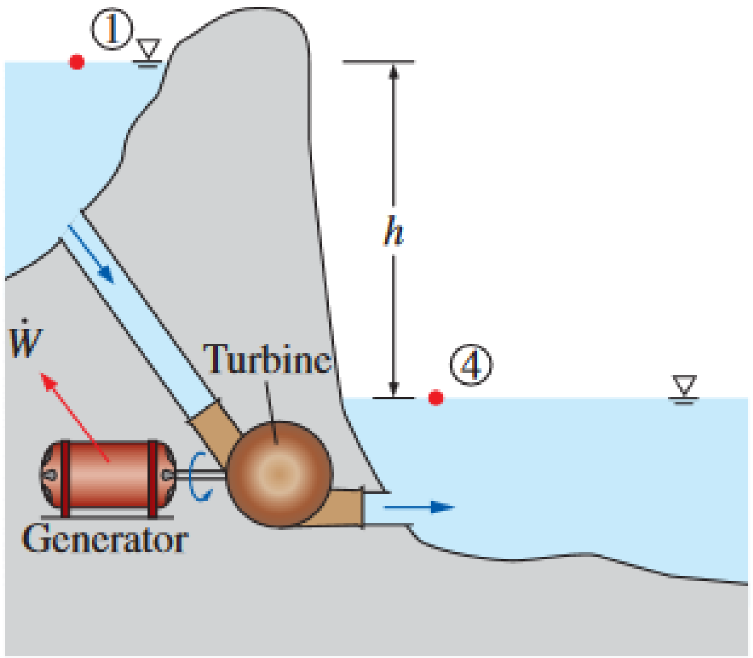
where P/ρ is the flow energy, $V^2/2$ is the kinetic energy, and gz is the potential energy of the fluid, all per unit mass. Then the mechanical energy change of a fluid during incompressible flow becomes

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad \text{(kJ/kg)}$$

MECHANICAL ENERGY AND EFFICIENCY

- Therefore, the mechanical energy of a fluid does not change during flow if its pressure, density, velocity, and elevation remain constant.

- In the absence of any irreversible losses, the mechanical energy change represents the mechanical work supplied to the fluid (if $\Delta e_{mech} > 0$) or extracted from the fluid (if $\Delta e_{mech} < 0$). The maximum (ideal) power generated by a turbine, for example, is Wmax = $\dot{m}\Delta e_{mech}$



$$\dot{W}_{max} = \dot{m}\Delta e_{mech} = \dot{m}g(z_1 - z_4) = \dot{m}gh$$

since $P_1 \approx P_4 = P_{atm}$ and $V_1 = V_4 \approx 0$

MECHANICAL ENERGY AND EFFICIENCY

- The transfer of mechanical energy is usually accomplished by a rotating shaft, and thus mechanical work is often referred to as shaft work.
- A pump or a fan receives shaft work (usually from an electric motor) and transfers it to the fluid as mechanical energy (less frictional losses). A turbine, on the other hand, converts the mechanical energy of a fluid to shaft work.
- Because of irreversibilities such as friction, mechanical energy cannot be converted entirely from one mechanical form to another, and the mechanical efficiency of a device or process is defined as

$$\eta_{\text{mech}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{\text{mech, out}}}{E_{\text{mech, in}}} = 1 - \frac{E_{\text{mech, loss}}}{E_{\text{mech, in}}}$$

- The degree of perfection of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the pump efficiency and turbine efficiency. In rate form, these are defined as

$$\eta_{\text{pump}} = \frac{\text{Mechanical power increase of the fluid}}{\text{Mechanical power input}} = \frac{\Delta \dot{E}_{\text{mech, fluid}}}{\dot{W}_{\text{shaft, in}}} = \frac{\dot{W}_{\text{pump}, u}}{\dot{W}_{\text{pump}}}$$

$$\Delta \dot{E}_{\text{mech, fluid}} = \dot{E}_{\text{mech, out}} - \dot{E}_{\text{mech, in}}$$

$$\eta_{\text{turbine}} = \frac{\text{Mechanical power output}}{\text{Mechanical power decrease of the fluid}} = \frac{\dot{W}_{\text{shaft, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{\dot{W}_{\text{turbine}}}{\dot{W}_{\text{turbine}, e}}$$

$$|\Delta \dot{E}_{\text{mech, fluid}}| = \dot{E}_{\text{mech, in}} - \dot{E}_{\text{mech, out}}$$

MECHANICAL ENERGY AND EFFICIENCY

- The mechanical efficiency should not be confused with the motor efficiency and the generator efficiency, which are defined as

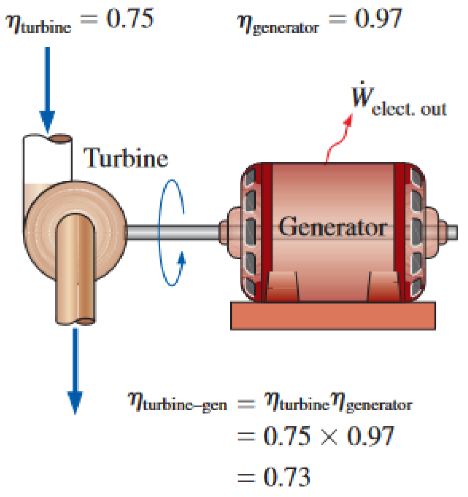
Motor:

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft, out}}}{\dot{W}_{\text{elect, in}}}$$

and

Generator:

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect, out}}}{\dot{W}_{\text{shaft, in}}}$$

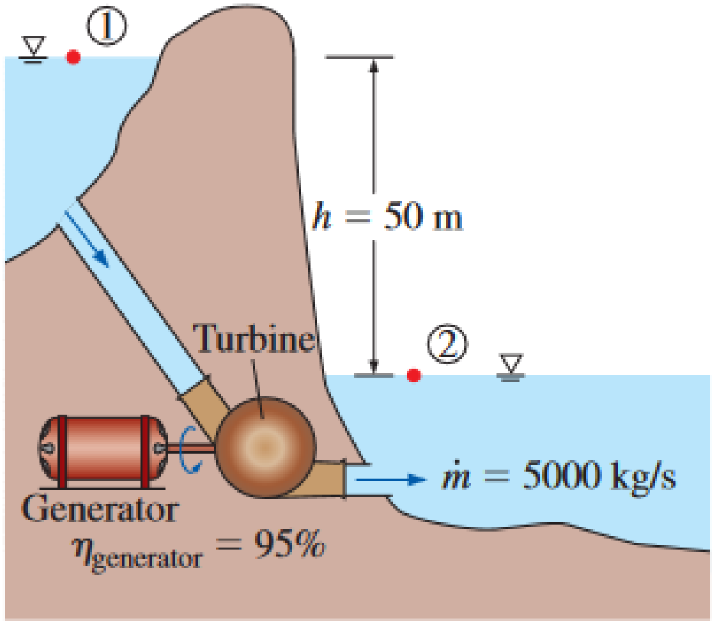


- A pump is usually packaged together with its motor, and a turbine with its generator. Therefore, we are usually interested in the combined or overall efficiency of pump–motor and turbine–generator combinations, which are defined as

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\,\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump, }u}}{\dot{W}_{\text{elect, in}}} = \frac{\Delta \dot{E}_{\text{mech, fluid}}}{\dot{W}_{\text{elect, in}}}$$

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\,\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect, out}}}{\dot{W}_{\text{turbine, }e}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|}$$

- **The water in a large lake is to be used to generate electricity by the installation of a hydraulic turbine–generator. The elevation difference between the free surfaces upstream and downstream of the dam is 50 m. Water is to be supplied at a rate of 5000 kg/s. If the electric power generated is measured to be 1862 kW and the generator efficiency is 95 percent, determine (a) the overall efficiency of the turbine–generator, (b) the mechanical efficiency of the turbine, and (c) the shaft power supplied by the turbine to the generator.**



Analysis (*a*) We perform our analysis from inlet (1) at the free surface of the lake to outlet (2) at the free surface of the downstream discharge site. At both free surfaces the pressure is atmospheric and the velocity is negligibly small. The change in the water's mechanical energy per unit mass is then

$$e_{\text{mech, in}} - e_{\text{mech, out}} = \underbrace{\cancel{\frac{P_{\text{in}} - P_{\text{out}}}{\rho}}}_{0} + \underbrace{\cancel{\frac{V_{\text{in}}^2 - V_{\text{out}}^2}{2}}}_{0} + g(z_{\text{in}} - z_{\text{out}})$$

$$= gh$$

$$= (9.81\ \text{m/s}^2)(50\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.491\frac{\text{kJ}}{\text{kg}}$$

Then the rate at which mechanical energy is supplied to the turbine by the fluid and the overall efficiency become

$$|\Delta \dot{E}_{\text{mech, fluid}}| = \dot{m}(e_{\text{mech, in}} - e_{\text{mech, out}}) = (5000\ \text{kg/s})(0.491\ \text{kJ/kg}) = 2455\ \text{kW}$$

$$\eta_{\text{overall}} = \eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{1862\ \text{kW}}{2455\ \text{kW}} = \mathbf{0.760}$$

(*b*) Knowing the overall and generator efficiencies, the mechanical efficiency of the turbine is determined from

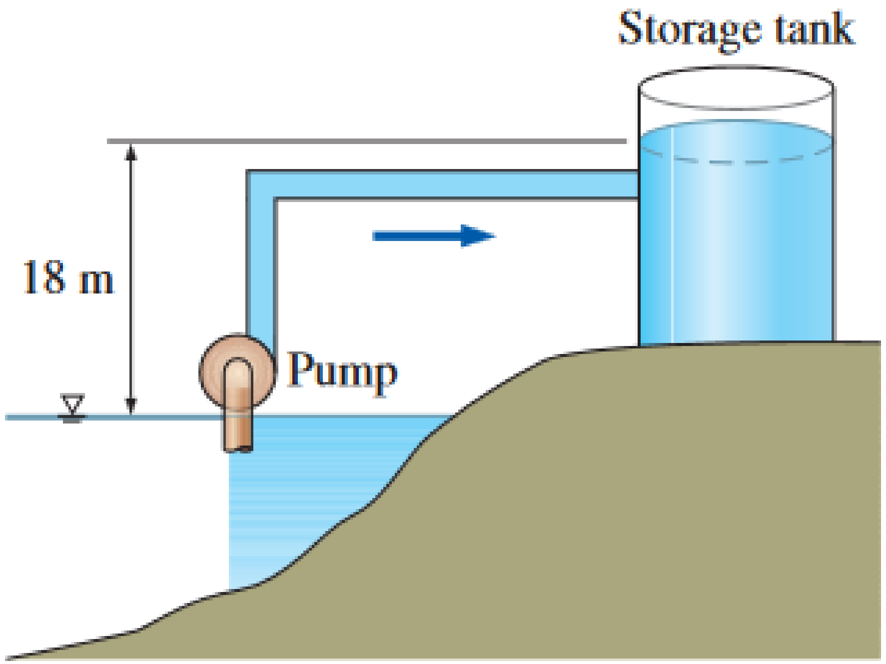
$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\,\eta_{\text{generator}} \rightarrow \eta_{\text{turbine}} = \frac{\eta_{\text{turbine-gen}}}{\eta_{\text{generator}}} = \frac{0.76}{0.95} = \mathbf{0.800}$$

(*c*) The shaft power output is determined from the definition of mechanical efficiency,

$$\dot{W}_{\text{shaft, out}} = \eta_{\text{turbine}}|\Delta \dot{E}_{\text{mech, fluid}}| = (0.800)(2455\ \text{kW}) = 1964\ \text{kW} \approx \mathbf{1960\ kW}$$

Discussion Note that the lake supplies 2455 kW of mechanical power to the turbine, which converts 1964 kW of it to shaft power that drives the generator, which generates 1862 kW of electric power. There are irreversible losses through each component. Irreversible losses in the pipes are ignored

- **Water is pumped from a lake to a storage tank 18 m above at a rate of 70 L/s while consuming 20.4 kW of electric power. Disregarding any frictional losses in the pipes and any changes in kinetic energy, determine (a) the overall efficiency of the pump–motor unit and (b) the pressure difference between the inlet and the exit of the pump.**



MECHANICAL ENGINEERING SCIENCE

Chapter 2 – IC Engines

Srinivasa Prasad K S
Department of Mechanical Engineering

The distinctive feature of our civilization today, one that makes it different from all others, is the wide use of mechanical power. At one time, the primary source of power for the work of peace or war was chiefly man's muscles. Later, animals were trained to help and afterwards the wind and the running stream were harnessed. But, the great step was taken in this direction when man learned the art of energy conversion from one form to another. The machine which does this job of energy conversion is called an ENGINE.

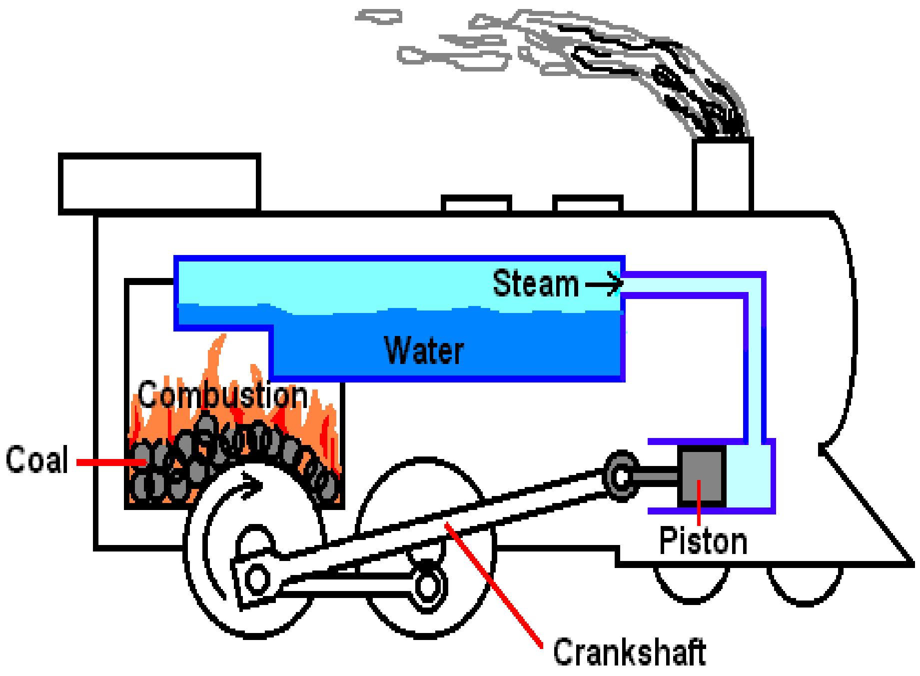
- **ENGINE –** An engine is a device which transforms one form of energy into another form.

- **HEAT ENGINE -** Heat engine is a device which transforms the chemical energy of a fuel into thermal energy and utilizes this thermal energy to perform useful work. Thus, thermal energy is converted to mechanical energy in a heat engine.

- Heat engines can be broadly classified into two categories:
  (i) Internal Combustion Engines (IC Engines)
  (ii) External Combustion Engines (EC Engines)

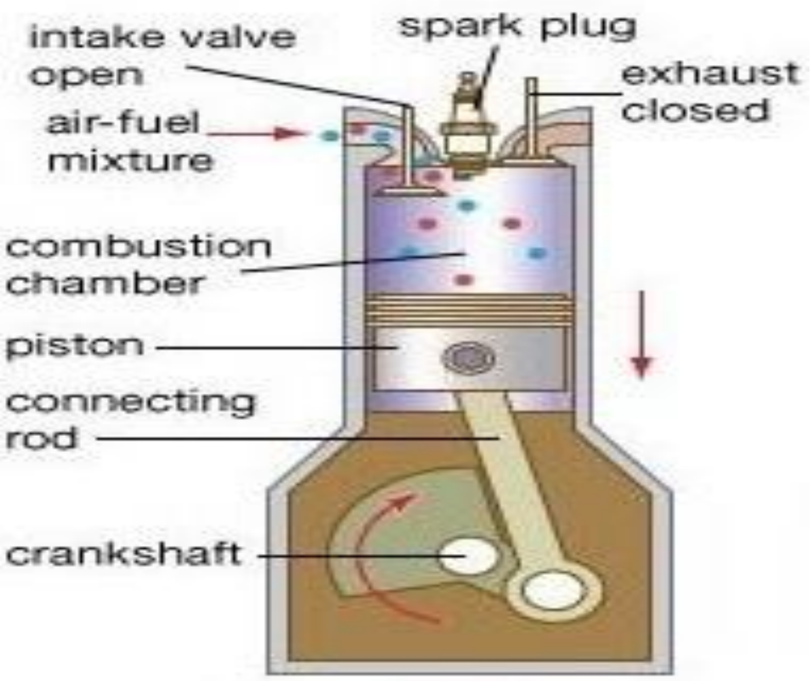
- External combustion engines are those in which combustion takes place outside the engine.

- For example, in a steam engine or a steam turbine, the heat generated due to the combustion of fuel is employed to generate high pressure steam which is used as the working fluid in a reciprocating engine or a turbine.



- Internal combustion engines are those in which combustion takes place within the engine.

- For example, in case of petrol or diesel engines, the products of combustion generated by the combustion of fuel and air within the cylinder form the working fluid.



intake
Air-fuel mixture is drawn in.

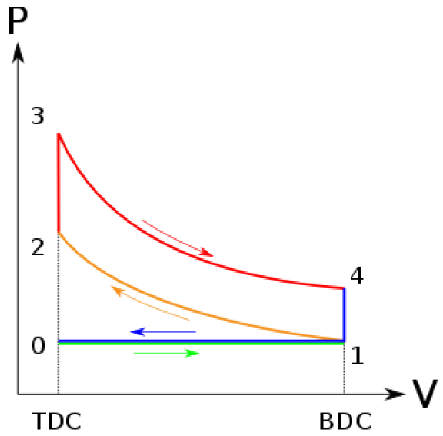
- **CLASSIFICATION OF IC ENGINES -** There are several criteria for classification of I.C. engines. Some of the important criteria can be explained as:
  - Number of strokes per cycle
  - Nature of thermodynamic cycle
  - Ignition systems
  - Fuel used
  - Arrangement of cylinders
  - Cooling systems
  - Fuel supply systems

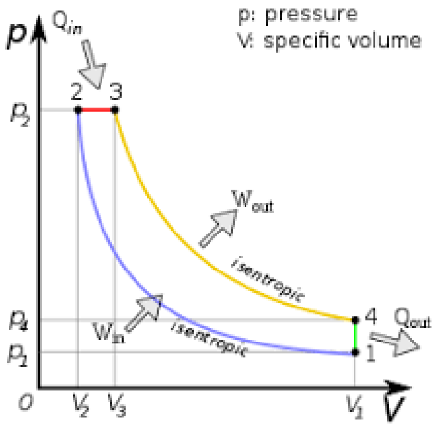
<u>Number of Strokes Per Cycle</u>:

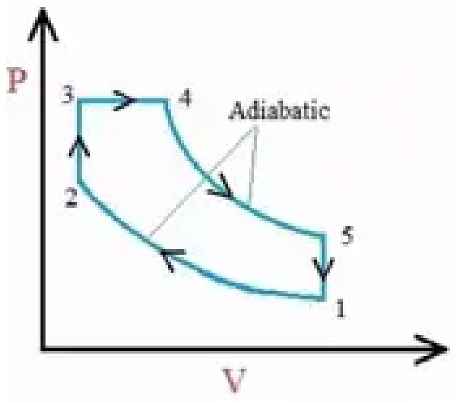
- I.C. engines can be classified as **four-stroke engines (4S)** and **two-stroke engines (2S).**
- In four-stroke engines, the thermodynamic cycle is completed in four strokes of the piston or two revolutions of the crankshaft whereas, in two-stroke engines, the thermodynamic cycle is completed in two strokes of the piston or one revolution of the crankshaft.

<u>Nature of Thermodynamic Cycle:</u>

- I.C. engines can be classified as **Otto cycle, Diesel cycle, and Dual cycle engines**.







Ignition Systems:

- There are two modes of ignition of fuel inside the cylinder — **spark ignition** and **compression ignition**.

- In spark ignition, sparking starts at the end of compression stroke from spark plug while in compression ignition the temperature of the fuel is increased to the self-ignition point by compressing the air alone and at the end of compression, fuel is injected into the cylinder.

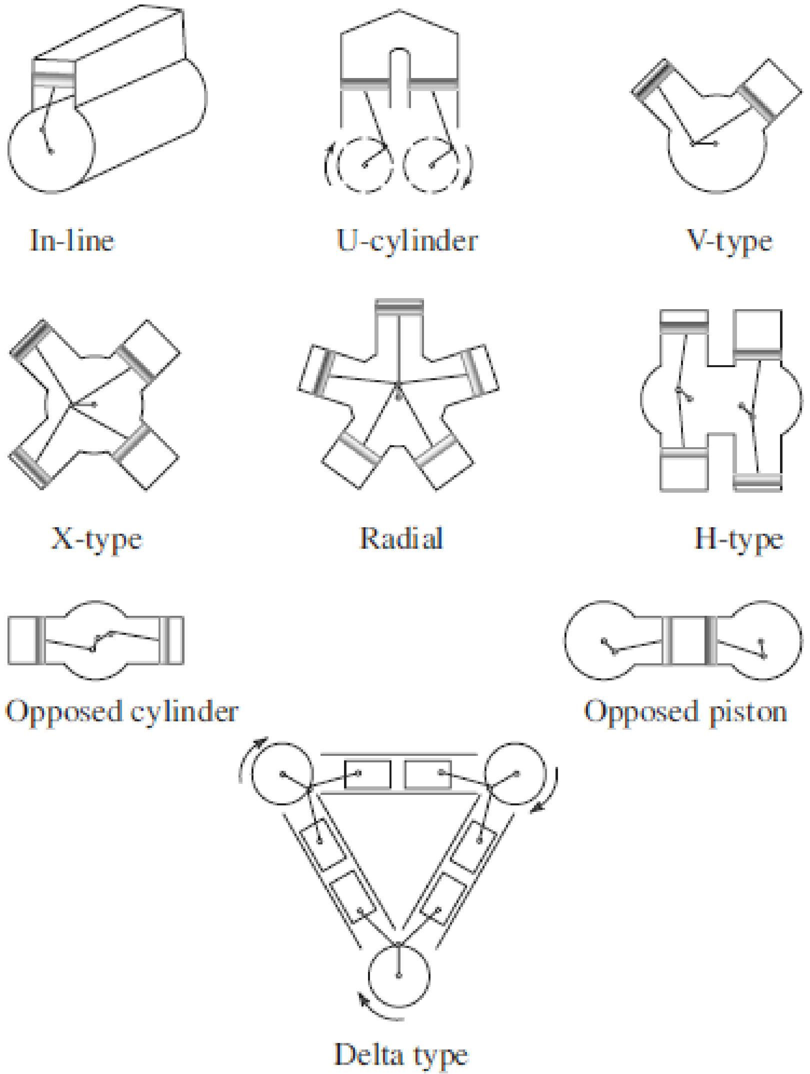
Fuel Used:

- On the basis of fuel used, I.C. Engines can be classified as (a) **Gas engines** like CNG, LPG, etc. (b) **Petrol engine**, (c) **Diesel engine**, and (d) **Bi-fuel engine**. In a bi-fuel engine, two types of fuels are used like gaseous fuel and liquid fuel.

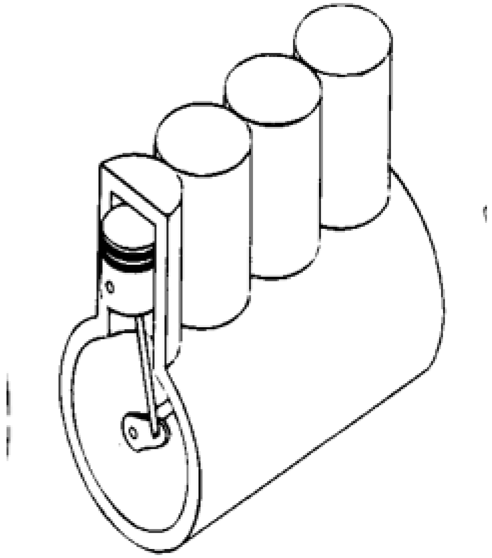
Arrangement of Cylinders:

- Another common method of classifying IC engines is by the cylinder arrangement. The cylinder arrangement is only applicable to multi cylinder engines.

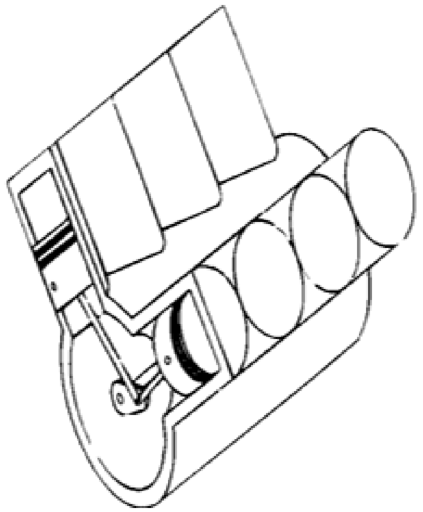
- A number of cylinder arrangements are popular with designers. The details of various cylinder arrangements are shown.



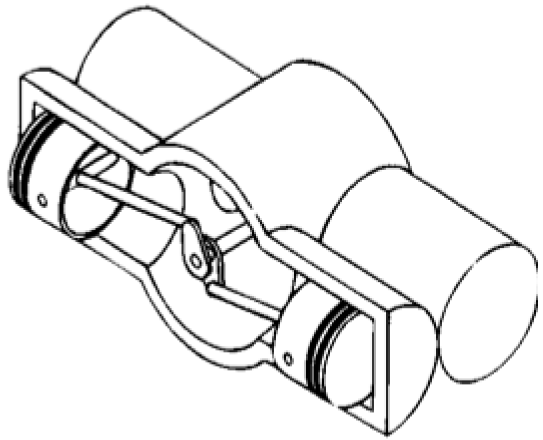
In-line Engine : The in-line engine is an engine with one cylinder bank, i.e. all cylinders are arranged linearly, and transmit power to a single crankshaft. This type is quite common with automobile engines. Four and six cylinder in-line engines are popular in automotive applications.



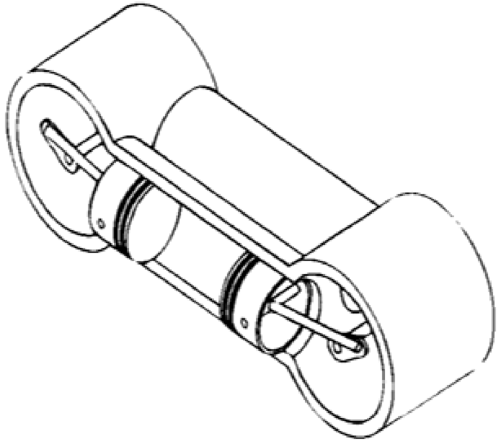
'V' Engine : In this engine there are two banks of cylinders (i.e., two in line engines) inclined at an angle to each other and with one crankshaft. Most of the high powered automobiles use the 8 cylinder 'V' engine, four in-line on each side of the 'V'. Engines with more than six cylinders generally employ this configuration.



Opposed Cylinder Engine : This engine has two cylinder banks located in the same plane on opposite sides of the crankshaft. It can be visualized as two 'in-line' arrangements 180 degrees apart. It is inherently a well balanced engine and has the advantages of a single crankshaft. This design is used in small aircrafts.



Opposed Piston Engine : When a single cylinder houses two pistons, each of which driving a separate crankshaft, it is called an opposed piston engine. The movement of the pistons is synchronized by coupling the two crankshafts. Opposed piston arrangement, like opposed cylinder arrangement is inherently well balanced.



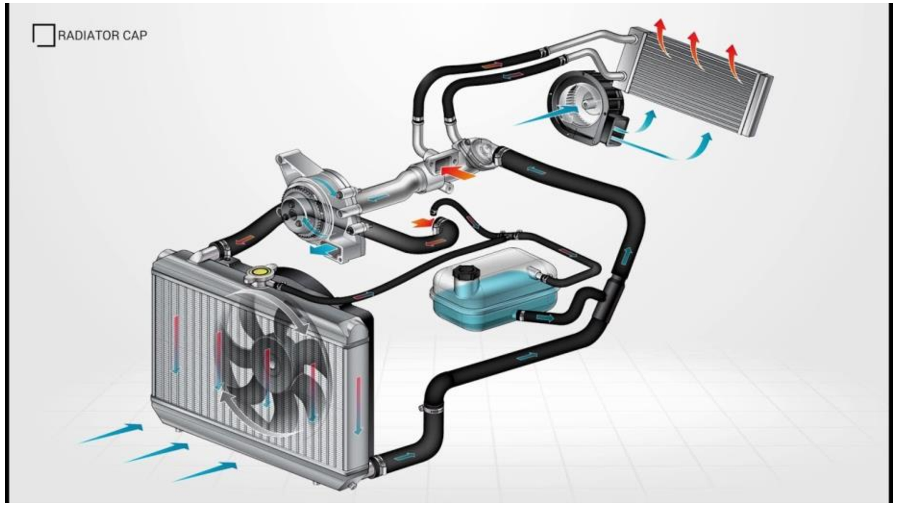
Radial Engine :

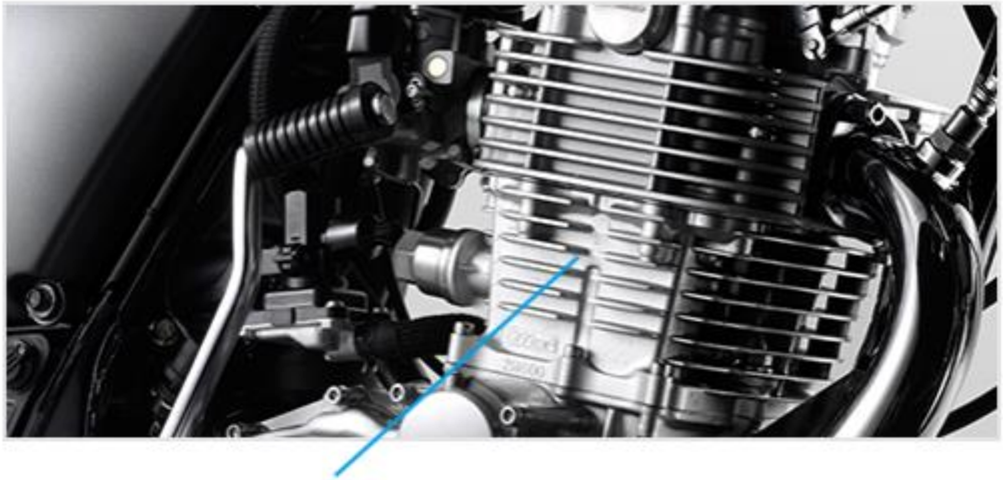
Radial engine is one where more than two cylinders in each row are equally spaced around the crankshaft. The radial arrangement of cylinders is most commonly used in conventional air-cooled aircraft engines. Pistons of all the cylinders are coupled to the same crankshaft.

Cooling Systems:

- There are two types of cooling systems in I.C. Engines—**water cooling** and **air cooling**.

- In water cooling, coolant and radiators are provided to cool the cylinder. In air cooling, fins are provided on the surface of the cylinder to radiate the heat into the atmosphere. Low power engines like motorbikes are equipped with air cooling systems, whereas large power producing engines like a car, bus, truck, etc. are equipped with water cooling systems.





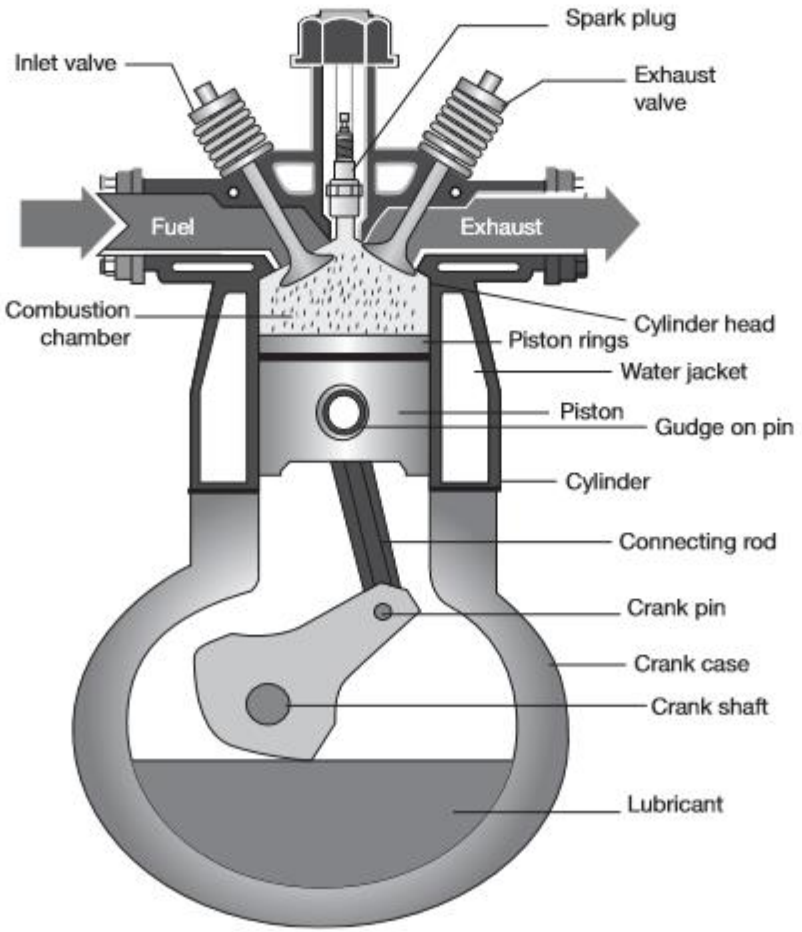
Fins on an air-cooled engine

Fuel Supply Systems:

- On the basis of fuel supply systems, I.C. Engines can be classified as:
  (a) Carburetor engine,
  (b) Air injection engine, and
  (c) Airless or solid or Mechanical injection engines.

- In a carburetor engine, air and fuel are properly mixed into the carburetor and then fed into the cylinder. In air injection engines, fuel is supplied to the cylinder with the help of compressed air. In mechanical injection engines, the fuel is injected into the cylinder with the help of mechanical pump and nozzle.

BASIC STRUCTURE OF AN IC ENGINE:

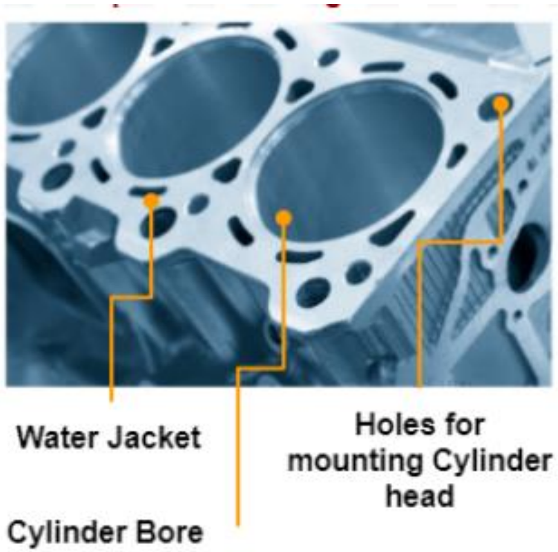


Cylinder:

- It is a hollow cylindrical structure closed at one end with the cylinder head.

- The combustion of the fuel takes place inside the cylinder. This is known as the heart of the engine. It is made of hard and high thermal conductivity materials by casting. A piston reciprocates inside the cylinder and produces power.

Cylinder Head: It covers one end of the cylinder and consists of valves/ports and spark plug/injector.



Piston:

- It is a cylindrical component which is fitted perfectly inside the cylinder providing a gas-tight space with the piston rings and the lubricant.

- The piston is connected to connecting rod by gudgeon pin. The main function of the piston is to transfer the power produced by combustion of the fuel to the crankshaft.

Piston Rings:

- The outer periphery of the piston is provided with several grooves into which piston rings are fitted. The piston is fitted with these rings. The upper ring is known as **compression ring** and the lower rings are known as **oil rings**.

- The function of the compression ring is to compress the air or air-fuel mixture and the function of the oil rings is to collect the surplus lubricating oil on the liner surface.

Connecting Rod:

- It connects the piston and the crankshaft. One end, called the small end, is connected to the gudgeon pin located in the piston and the other end, called big end, is connected to crank pin.

- The function of the connecting rod is to transfer the reciprocating motion of the piston into rotary motion of the crankshaft.

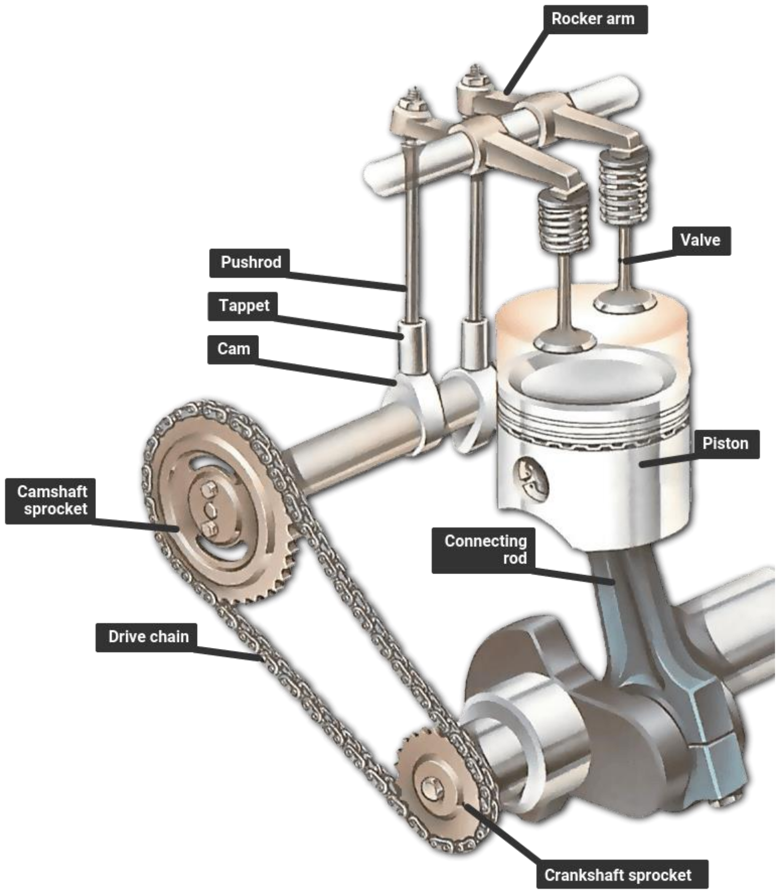
Crankshaft:

- It is principal rotating part of the engine which controls the sequence of reciprocating motion of the pistons. It consists of several bearings and crank pins.

Valves:

- Normally, the two valves are used for each cylinder, which may be of mushroom shaped poppet type.

- They are provided on the cylinder head for regulating the charge coming into the cylinder and for discharging the products of combustion from the cylinder. The valve mechanism consists of cams, cam follower, push rod, rocker arms, and spring.

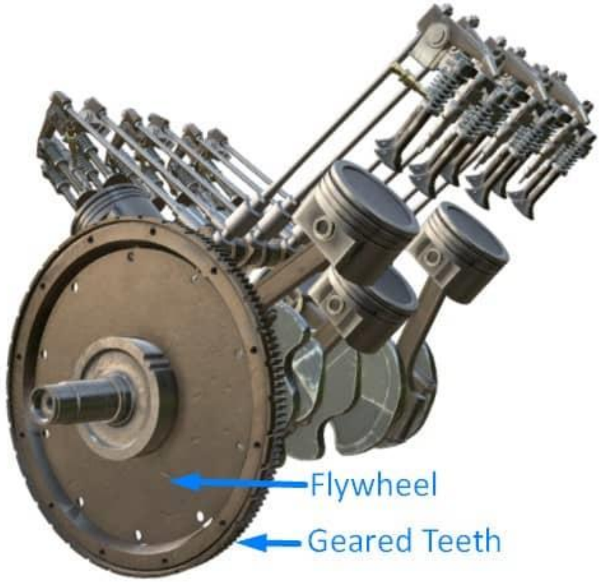


Crankcase:

- The bottom portion of the cylinder block is called crankcase. A cover called crankcase which becomes a sump for lubricating oil is fastened to the bottom of the cylinder block.

Flywheel:

- It is a heavy wheel mounted on the crankshaft to minimize the cyclic variations in speed. It absorbs the energy during the power stroke and releases it during the non-power stroke.



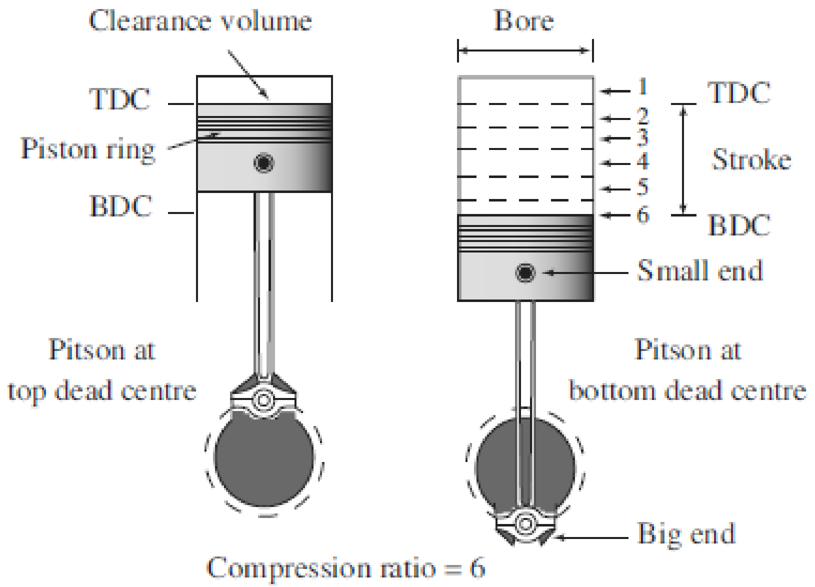
NOMENCLATURE:

Cylinder Bore (d) : The nominal inner diameter of the working cylinder is called the cylinder bore and is designated by the letter d.

Piston Area (A) : The area of a circle of diameter equal to the cylinder bore is called the piston area and is designated by the letter A.

Stroke (L) : The nominal distance through which a working piston moves between two successive reversals of its direction of motion is called the stroke and is designated by the letter L.

Dead Centre : The position of the working piston and the moving parts which are mechanically connected to it, at the moment when the direction of the piston motion is reversed at either end of the stroke is called the dead centre.



NOMENCLATURE:

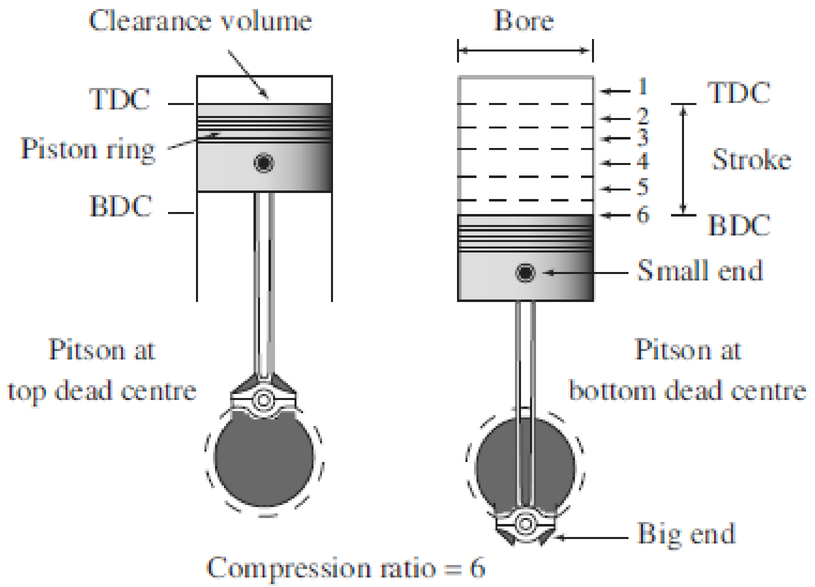
There are two dead centres in the engine as indicated in Fig. They are:

(i) Top Dead Centre (ii) Bottom Dead Centre

(i) Top Dead Centre (TDC) : It is the dead centre when the piston is farthest from the crankshaft.

(ii) Bottom Dead Centre (BDC) : It is the dead centre when the piston is nearest to the crankshaft.

Displacement or Swept Volume (Vs) : The nominal volume swept by the working piston when travelling from one dead centre to the other is called the displacement volume. It is usually expressed in terms of cubic centimeter (cc).



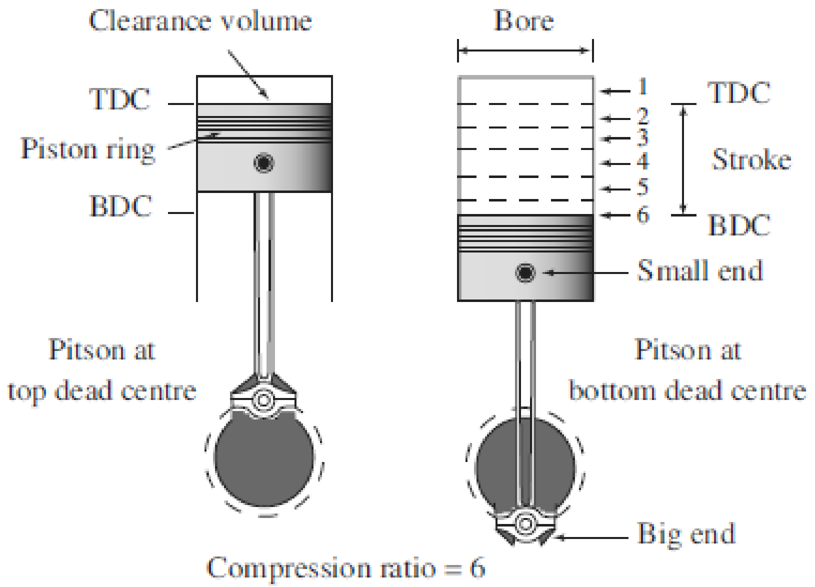
$$V_s = A \times L = \frac{\pi}{4} d^2 L$$

NOMENCLATURE:

Clearance Volume (Vc): The nominal volume of the combustion chamber above the piston when it is at the top dead centre is the clearance volume.

Compression Ratio (r) : It is the ratio of the total cylinder volume when the piston is at the bottom dead centre, Vt , to the clearance volume, Vc.

$$r = \frac{V_T}{V_C} = \frac{V_C + V_s}{V_C} = 1 + \frac{V_s}{V_C}$$

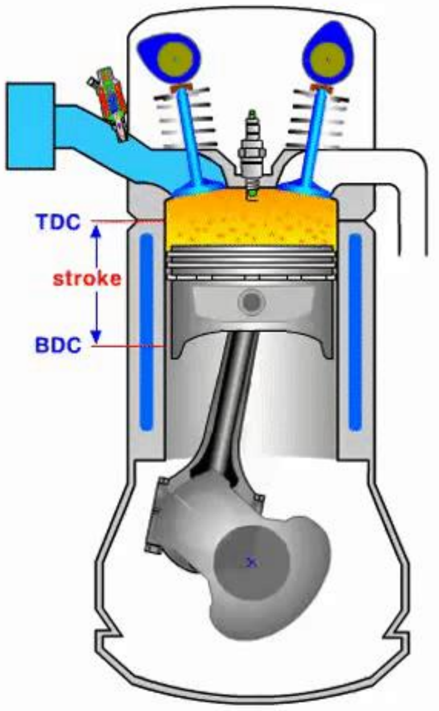


WORKING PRINCIPLE OF 4S PETROL ENGINE (SPARK IGNITION ENGINE)

- In a four-stroke engine, the cycle of operations is completed in **four strokes** of the piston or **two revolutions** of the crankshaft.

- During the four strokes, there are five events to be completed, viz., suction, compression, combustion, expansion and exhaust. Each stroke consists of 180° of crankshaft rotation and hence a four-stroke cycle is completed through 720° of crank rotation.

- The cycle of operation for an ideal four-stroke SI engine consists of the following four strokes :
  (i) suction or intake stroke;
  (ii) compression stroke;
  (iii) expansion or power stroke and
  (iv) exhaust stroke.



WORKING PRINCIPLE OF 4S PETROL ENGINE

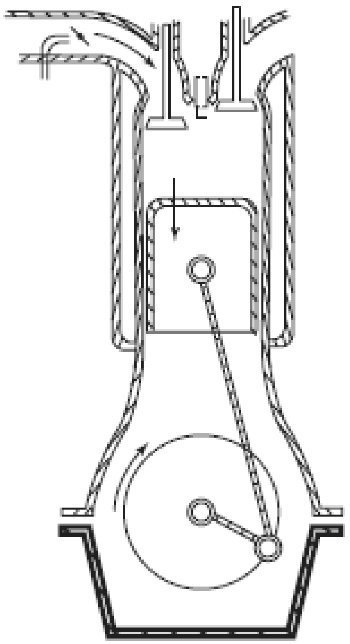
Suction Stroke:

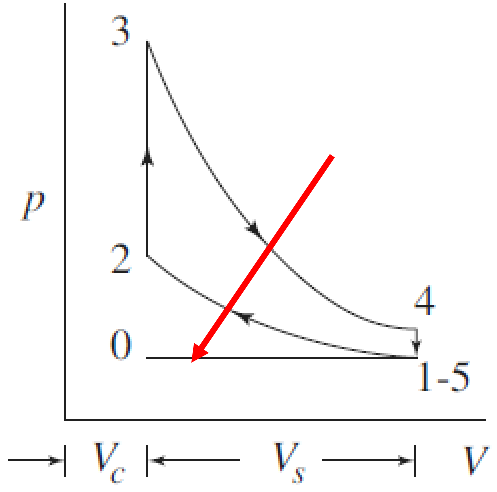
- Suction stroke 0→1 starts when the piston is at the top dead centre and about to move downwards.

- The inlet valve is assumed to open instantaneously and at this time the exhaust valve is in the closed position.

- Due to the suction created by the motion of the piston towards the bottom dead centre, the charge consisting of fuel-air mixture is drawn into the cylinder.

- When the piston reaches the bottom dead centre the suction stroke ends and the inlet valve closes instantaneously.

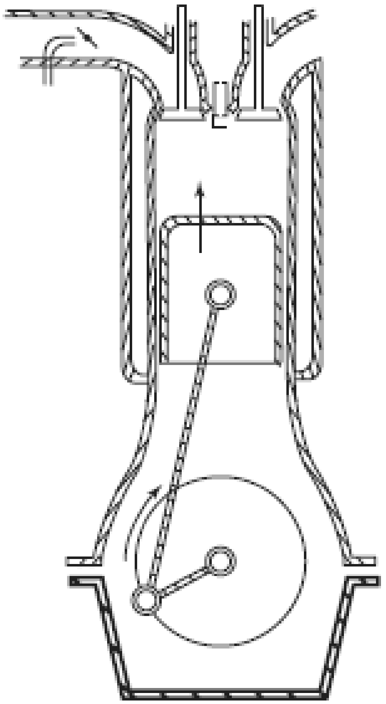


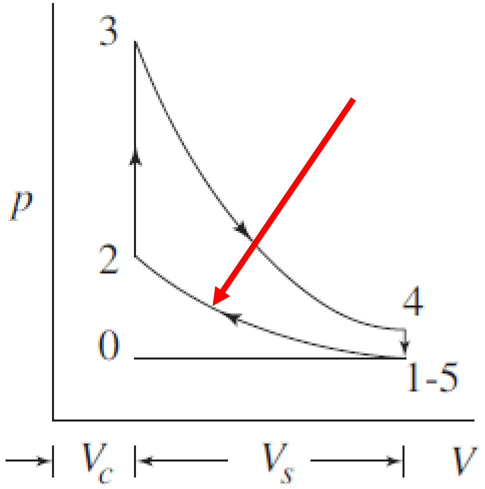


WORKING PRINCIPLE OF 4S PETROL ENGINE

Compression Stroke:

- The charge taken into the cylinder during the suction stroke is compressed by the return stroke of the piston 1→2.
- During this stroke both inlet and exhaust valves are in closed position.
- The mixture which fills the entire cylinder volume is now compressed into the clearance volume.





WORKING PRINCIPLE OF 4S PETROL ENGINE

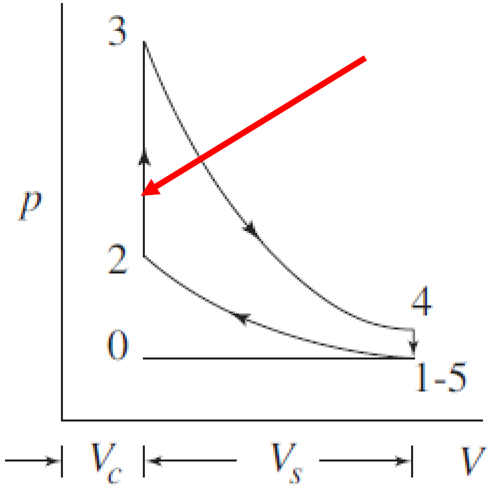
Compression Stroke:

- At the end of the compression stroke the mixture is ignited with the help of a spark plug located on the cylinder head.

- In ideal engines it is assumed that burning takes place instantaneously when the piston is at the top dead centre and hence the burning process can be approximated as **heat addition at constant volume**.

- During the burning process the chemical energy of the fuel is converted into heat energy producing a temperature rise of about 2000°C (process 2→3).

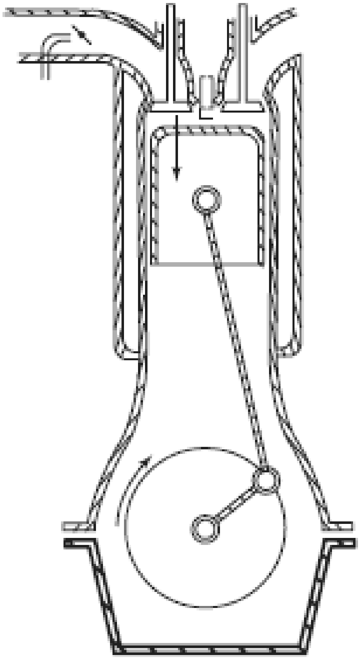
- The pressure at the end of the combustion process is considerably increased due to the heat release from the fuel.

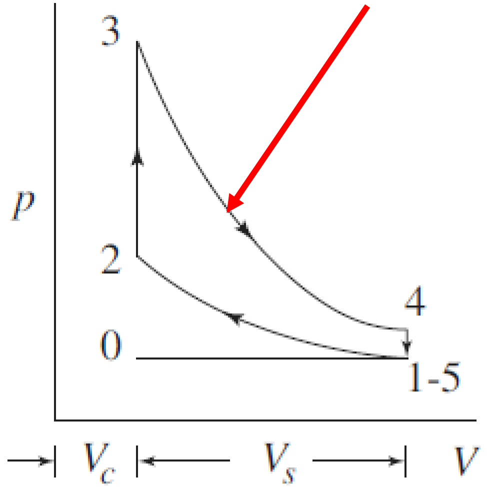


WORKING PRINCIPLE OF 4S PETROL ENGINE

Expansion or Power Stroke :

- The high pressure of the burnt gases forces the piston towards the BDC, (stroke 3→4).
- Both the valves are in closed position.
- Of the four-strokes only during this stroke power is produced. Both pressure and temperature decrease during expansion.

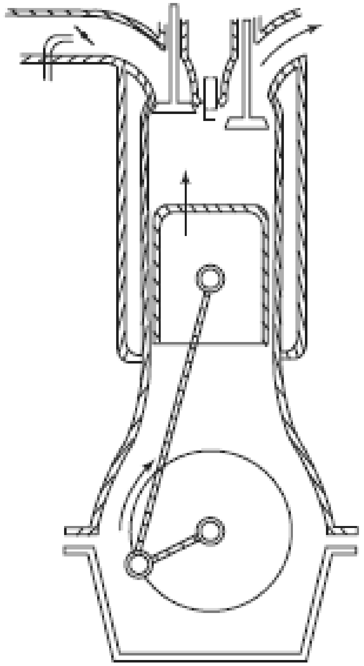


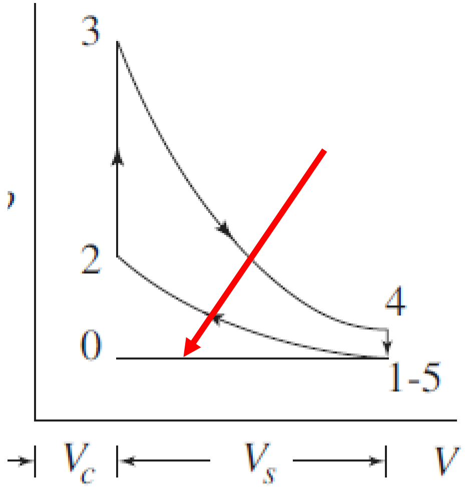


WORKING PRINCIPLE OF 4S PETROL ENGINE

Exhaust Stroke:

- At the end of the expansion stroke the exhaust valve opens instantaneously and the inlet valve remains closed.
- The pressure falls to atmospheric level a part of the burnt gases escape.
- The piston starts moving from the bottom dead centre to top dead centre (stroke 5→0) and sweeps the burnt gases out from the cylinder almost at atmospheric pressure.
- The exhaust valve closes when the piston reaches TDC.





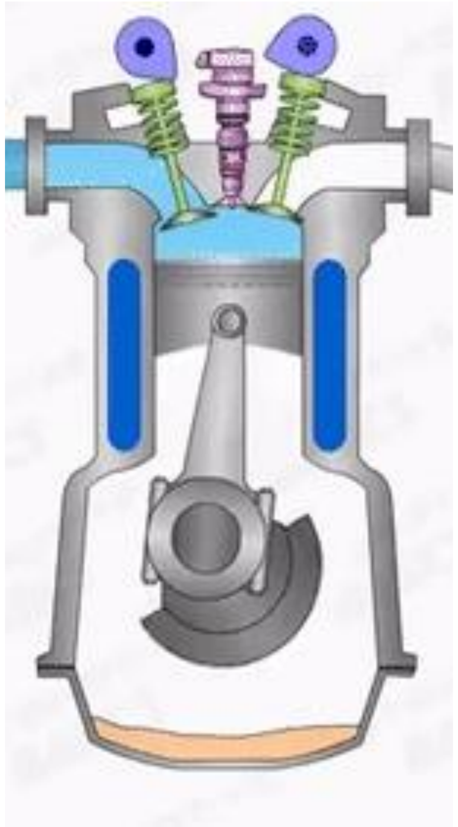
WORKING PRINCIPLE OF 4S DIESEL ENGINE (COMPRESSION IGNITION ENGINE)

- The four-stroke CI engine is similar to the four-stroke SI engine but it operates at a much higher compression ratio. The compression ratio of an SI engine is between 6 and 10 while for a CI engine it is from 16 to 20.

- In the CI engine during suction stroke, air, instead of a fuel-air mixture, is inducted.

- Due to higher compression ratios employed, the temperature at the end of the compression stroke is sufficiently high to self ignite the fuel which is injected into the combustion chamber.

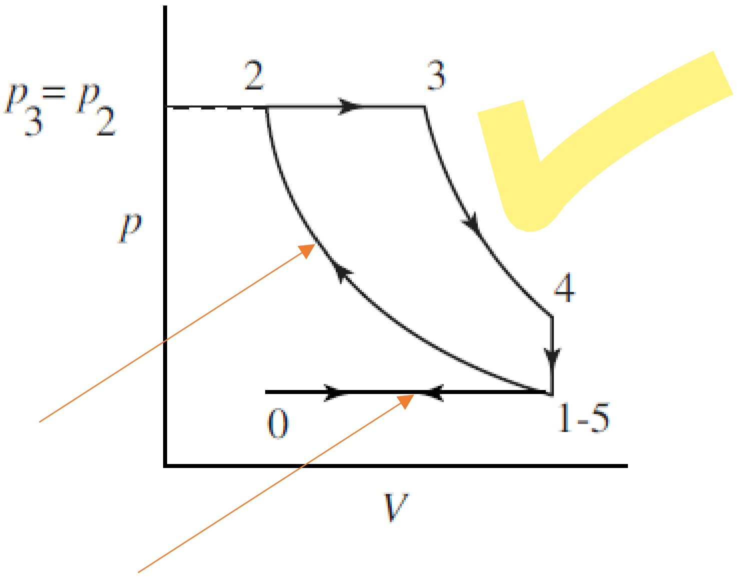
- In CI engines, a high pressure fuel pump and an injector are provided to inject the fuel into the combustion chamber. The carburettor and ignition system necessary in the SI engine are not required in the CI engine.

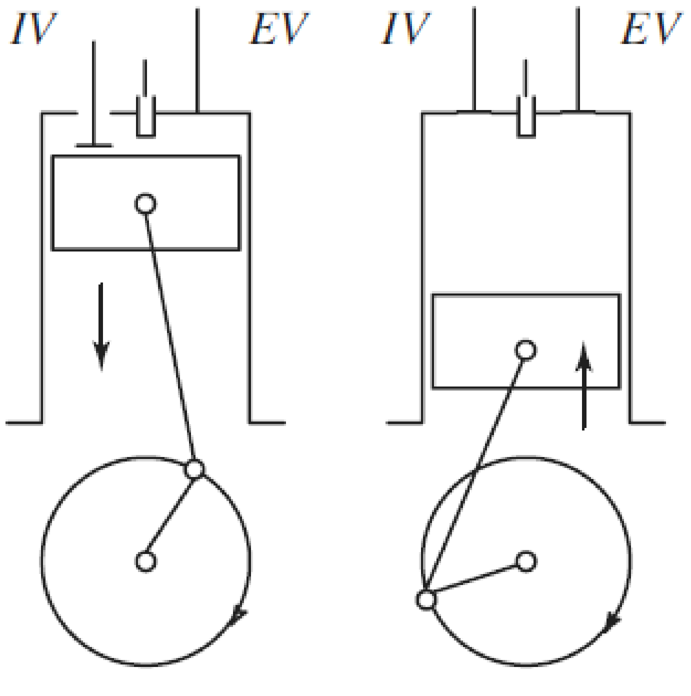


WORKING PRINCIPLE OF 4S DIESEL ENGINE

Suction Stroke: Air alone is inducted during the suction stroke. During this stroke inlet valve is open and exhaust valve is closed.

Compression Stroke: Air inducted during the suction stroke is compressed into the clearance volume. Both valves remain closed during this stroke.





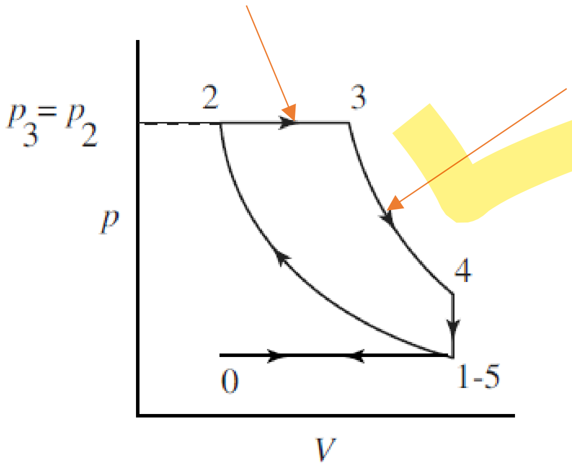
(a) Suction (b) Compression

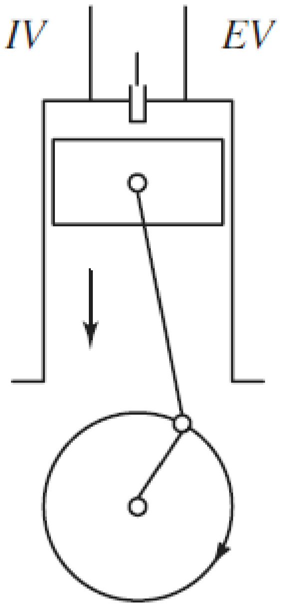
WORKING PRINCIPLE OF 4S DIESEL ENGINE

Expansion Stroke : Fuel injection starts nearly at the end of the compression stroke.

The rate of injection is such that combustion maintains the pressure constant in spite of the piston movement on its expansion stroke increasing the volume. Heat is assumed to have been added at **constant pressure**.

After the injection of fuel is completed (i.e. after cut-off) the products of combustion expand. Both the valves remain closed during the expansion stroke.





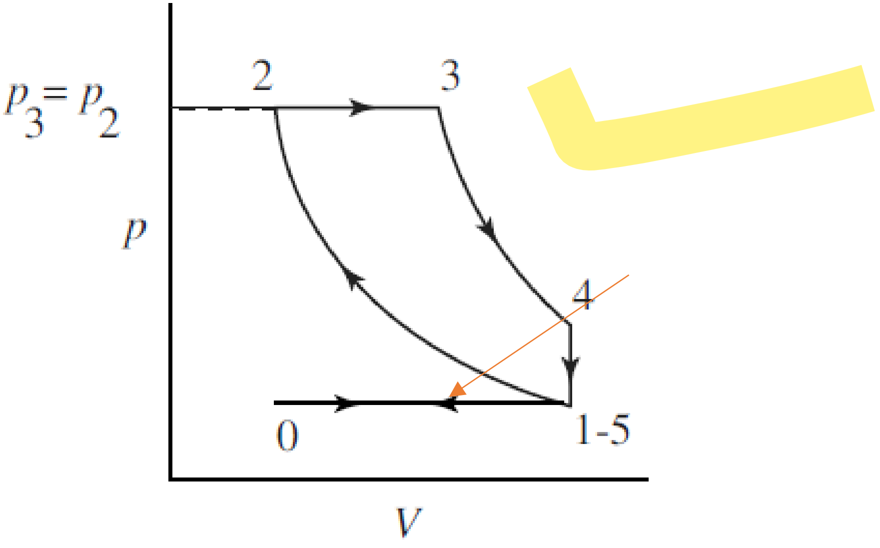
(c) Expansion

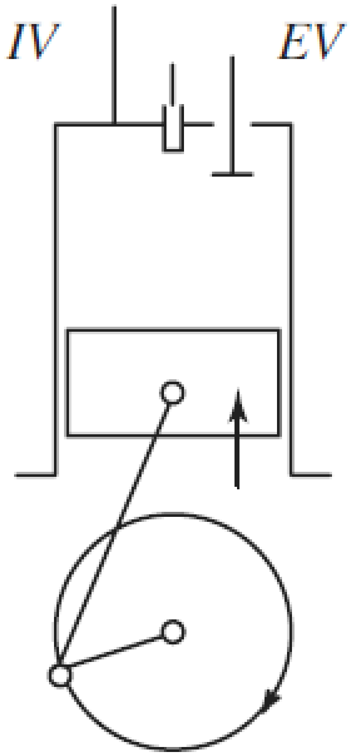
WORKING PRINCIPLE OF 4S DIESEL ENGINE

Exhaust Stroke :

The piston travelling from BDC to TDC pushes out the products of combustion.

The exhaust valve is open and the intake valve is closed during this stroke.





(d) Exhaust

COMPARISON OF PETROL AND DIESEL ENGINES

Description	Petrol Engine (SI Engine)	Diesel Engine (CI Engine)
Basic cycle	Works on **Otto cycle** or constant volume heat addition cycle.	Works on **Diesel cycle** or constant pressure heat addition cycle.
Fuel	Petrol, a highly volatile fuel. Self-ignition temperature is high.	Diesel oil, a non-volatile fuel. Self-ignition temperature is comparatively low.
Introduction of fuel	A gaseous mixture of fuel-air is introduced during the suction stroke. A carburettor and an ignition system are necessary. Modern engines have petrol injection	Fuel is injected directly into the combustion chamber at high pressure at the end of the compression stroke. A fuel pump and injector are necessary.

COMPARISON OF PETROL AND DIESEL ENGINES

Description	Petrol Engine (SI Engine)	Diesel Engine (CI Engine)
Ignition	Requires an ignition system with spark plug in the combustion chamber.	Self-ignition occurs due to high temperature of air because of the high compression.
Compression ratio	6 to 10. Upper limit is fixed by antiknock quality of the fuel.	16 to 20. Upper limit is limited by weight increase of the engine.
Speed	Due to light weight they are high speed engines.	Due to heavy weight they are low speed engines.
Thermal efficiency	Because of the lower CR, the maximum value of thermal efficiency that can be obtained is lower.	Because of higher CR, the maximum value of thermal efficiency that can be obtained is higher.

COMPARISON OF PETROL AND DIESEL ENGINES

Description	Petrol Engine (SI Engine)	Diesel Engine (CI Engine)
Weight	Lighter due to comparatively lower peak pressures.	Heavier due to comparatively higher peak pressures.

APPLICATIONS OF IC ENGINES

- The most important application of IC engines is in transport on land, sea and air. Other applications include industrial power plants and as prime movers for electric generators.

4S Petrol Engines:

- The most important application of small four-stroke petrol engines is in automobiles. A typical automobile is powered by a four-stroke four cylinder engine developing an output in the range of 30-60 kW at a speed of about 4500 rpm.

- Another application of four-stroke petrol engine is in small pumping sets and mobile electric generating sets.

- Smaller aircrafts normally employ four-stroke gasoline (SI) radial engines.

APPLICATIONS OF IC ENGINES

4S Diesel Engines:

- The four-stroke diesel engine is one of the most efficient and versatile prime movers. It is manufactured in sizes from 50 mm to more than 1000 mm of cylinder diameter and with engine speeds ranging from 100 to 4500 rpm while delivering outputs from 1 to 35000 kW.

- Small diesel engines are used in pump sets, construction machinery, air compressors, drilling rigs and many miscellaneous applications.

- Tractors for agricultural application use about 30 kW diesel engines whereas jeeps, buses and trucks use 40 to 100 kW diesel engines.

- Diesel engines are used both for mobile and stationary electric generating plants of varying capacities.

PERFORMANCE PARAMETERS OF IC ENGINES

- The following factors are to be considered in evaluating the performance of an engine:

  (i) **Maximum power or torque**

  (ii) **Specific fuel consumption**

  (iii) **Reliability and durability**

- Engine performance characteristics can be determined by the following two methods.

  (i) By using **experimental results** obtained from engine tests.

  (ii) By **analytical calculation** based on theoretical data.

PERFORMANCE PARAMETERS OF IC ENGINES

Engine Power

- The energy flow through the engine is expressed in three distinct terms. They are indicated power, IP, friction power FP and brake power, BP.

- Indicated power can be computed from the measurement of forces in the cylinder and brake power may be computed from the measurement of forces at the crankshaft of the engine. Friction power can be calculated with the above two values.

PERFORMANCE PARAMETERS OF IC ENGINES

ii) Indicated Power - The power developed inside the cylinder of the engine is called the indicated power (IP).

PERFORMANCE PARAMETERS OF IC ENGINES

iii) Brake Power – It is the net power available at the crank shaft of the engine for performing useful work (BP).

- It is always less than indicated power since a part of the power developed in the engine cylinder is used to overcome the frictional losses at different moving parts of the engine.
- Brake power of an engine can be determined by a brake of some kind applied to the brake pulley of the engine. The arrangement used for determination of BP of the engine is known as dynamometer. Usually, **rope brake dynamometer** is used for this purpose.
- BP is given by,

$$BP = \frac{2\pi NT}{60\times1000} \qquad (expressed\ in\ kW)$$

where
N = Crank speed in rpm; T = Torque in N-m

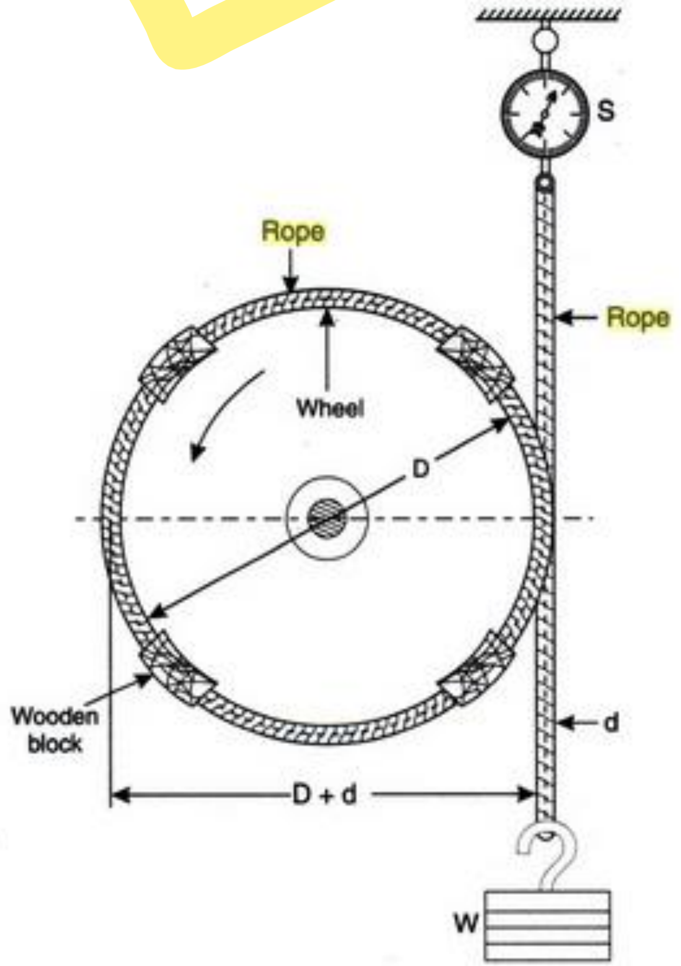
PERFORMANCE PARAMETERS OF IC ENGINES

- The rope brake dynamometer consists of rope wrapped round the brake drum or flywheel keyed to crankshaft of an engine whose BP is to be determined.

- One end of the rope is connected to the spring balance (with reading ‘S’) while at the other end is hung a weight W.

- Wooden blocks are incorporated to check the rope slipping off the brake drum/flywheel.

- It is evident from the figure that the net brake load which opposes the rotation is (W-S) and the effective radius at which the net load acts = (D+d)/2, where D is the diameter of the brake drum and d is the diameter of the rope.



PERFORMANCE PARAMETERS OF IC ENGINES

- Therefore,

$\therefore$ Braking torque,

$$T = \text{Frictional force} \times \text{radius} = (W - S)\left(\frac{D+d}{2}\right) \text{ Nm.}$$

$$\therefore \text{ Brake power, B.P.} = \frac{(W-S)\pi(D+d)N}{60 \times 10^3} \text{ kW}$$

PERFORMANCE PARAMETERS OF IC ENGINES

iv) Friction Power – It is the difference between the indicated power and brake power.

$$FP = IP - BP$$

- Apart from expressing engine performance in terms of power, it is also essential to express in terms of efficiencies.

v) Mechanical efficiency - Mechanical efficiency takes into account the mechanical losses in an engine like friction losses in case of pistons, bearings, gears, valve mechanisms, losses due to absorption of power by fuel pump, oil pump, radiator etc. In general, mechanical efficiency of engines varies from 65 to 85%.

It is defined as the ratio of brake power to indicated power.

$$\eta_{mech} = \frac{Brake\ power\ (BP)}{Indicated\ power\ (IP)}$$

PERFORMANCE PARAMETERS OF IC ENGINES

vi) Thermal efficiency – It gives an idea of the output generated by the engine with respect to heat supplied in the form of fuel.

- Thermal efficiency is expressed in two ways, viz., **indicated thermal efficiency** and **brake thermal efficiency.**

- **Indicated thermal efficiency =** $\eta_{ith} = \dfrac{IP}{CV \times m_f}$

- **Brake thermal efficiency** = $\eta_{bth} = \dfrac{BP}{CV \times m_f} \times 100$

CV is the calorific value of the fuel in KJ/kg and m_f is mass flow rate of the fuel in kg/s. IP and BP are in kW.

PERFORMANCE PARAMETERS OF IC ENGINES

vii) Specific fuel consumption – It is the mass of fuel consumed per kW of power developed per hour and is a criterion of economical power production.

- Specific fuel consumption is expressed in two ways, viz., **indicated specific fuel consumption (ISFC)** and **brake specific fuel consumption (BSFC).**

- **ISFC** = $\dfrac{\textit{Mass of fuel consumed in kg/hr}}{\textit{Indicated Power in kW}}$

- **BSFC** = $\dfrac{\textit{Mass of fuel consumed in kg/hr}}{\textit{Brake Power in kW}}$

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

1) The following data refers to a test on a single cylinder engine working on four stroke cycle:

   Diameter of brake drum = 60 cm
   Rope diameter = 3 cm
   Load on brake drum = 25 kg
   Spring balance reading = 5 kg
   Speed of engine = 400 rpm
   Bore = 10 cm
   Stroke = 15 cm
   Indicated Power = 3.141 kW

   Calculate (i) Brake Power (ii) Mechanical Efficiency

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

1) Brake Power (BP)

$$\text{Torque} = T = (W - S) \times \left(\frac{D_b + d_r}{2}\right) = (25 - 5) \times 9.81 \times \left(\frac{0.6 + 0.03}{2}\right) = 61.803\ Nm$$

$$\text{Brake Power} = BP = \frac{2\pi NT}{60 \times 1000} = \frac{2 \times \pi \times 400 \times 61.803}{60 \times 1000} = 2.589\ kW$$

2) Mechanical Efficiency

$$\eta_{mech} = \frac{BP}{IP} = \frac{2.589}{3.141} = 0.8241\ or\ 82.41\%$$

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

2) The following observations are taken during a trial on four stroke diesel engine.

Cylinder diameter = 25 cm
Stroke = 40 cm
Speed = 250 rpm
Brake load = 70 kg
Brake drum diameter = 2m
Diesel oil consumption = 0.1 litres/min
Specific gravity of fuel = 0.78
Calorific value of fuel = 43900 kJ/kg
Indicated Power = 24.54 kW

Determine (i) Brake Power (ii) Mechanical efficiency (iii) Brake thermal efficiency (iv) Indicated thermal efficiency.

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

Solution:

1) **Brake Power**

We know that brake power is given by

$$BP = \frac{2\pi NT}{60000} = \frac{2\times\pi\times250\times70\times9.81\times1}{60000} = 17.98\ kW$$

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

Solution:

2) Mechanical efficiency

We know that mechanical efficiency is given by,

$$\eta_{mech} = \frac{BP}{IP} = 73.3\%$$

3) Brake Thermal Efficiency

We know that brake thermal efficiency is given by,

$$\eta_{Bth} = \frac{BP}{m_f \times CV} = \frac{17.98}{\frac{0.1\times0.78\times1000}{1000\times60}\times43900} = 31.5\%$$

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

Solution:

4) Indicated Thermal Efficiency

We know that indicated thermal efficiency is given by,

$$\eta_{Ith} = \frac{IP}{m_f \times CV} = \frac{24.54}{\frac{0.1 \times 0.78 \times 1000}{1000 \times 60} \times 43900} = 43\%$$

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

3) A four cylinder four stroke petrol engine develops 30 kW at 2500 rpm. The mean effective pressure on each piston is 8 bar and mechanical efficiency is 80%. Calculate the diameter and stroke of each cylinder.

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

Solution:

We know that,

$$\eta_{mech} = \frac{BP}{IP}$$

Therefore,

$$IP = \frac{BP}{\eta_{mech}} = \frac{30}{0.8} = 37.5\ kW$$

Also, $IP = \frac{np_m LANK}{60 \times 1000}$

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

Solution:

$$37.5 = \frac{4 \times 8 \times 10^5 \times L \times (\frac{\pi}{4} d^2) \times 2500 \times (\frac{1}{2})}{60 \times 1000}$$

$$7.16 \times 10^{-4} = Ld^2$$

From data, L/d = 1.5 or L = 1.5d

Therefore,

$$7.16 \times 10^{-4} = (1.5d)d^2$$

This gives, d = 0.078 m = 78 mm; L = 1.5d = 117 mm

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

4) A diesel engine develops 5 kW. Its indicated thermal efficiency is 30% and mechanical efficiency is 75%. Estimate the fuel consumption of the engine in a) kg/hr and b) litres/hr. Also find ISFC and BSFC. Take CV of fuel = 42000 kJ/kg and specific gravity of fuel = 0.87.

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

Solution:

We have,

$$\eta_{mech} = \frac{BP}{IP}$$

$$Therefore, IP = \frac{BP}{\eta_{mech}} = \frac{5}{0.75} = 6.67 kW$$

We know that,

$$\eta_{ITH} = \frac{IP}{m_f \times CV}$$

$$Therefore, m_f = \frac{IP}{\eta_{ITH} \times CV}$$

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

Solution:

We have,

$$\eta_{mech} = \frac{BP}{IP}$$

$$Therefore, IP = \frac{BP}{\eta_{mech}} = \frac{5}{0.75} = 6.67 kW$$

We know that,

$$\eta_{ITH} = \frac{IP}{m_f \times CV}$$

$$Therefore, m_f = \frac{IP}{\eta_{ITH} \times CV}$$

PERFORMANCE PARAMETERS OF IC ENGINES - NUMERICALS

Solution:

So,

$$m_f = \frac{6.67}{0.3 \times 42000} = 5.293 \times 10^{-4} kg/s = 1.9057 kg/hr$$

To get fuel consumption in litres/hr,

$$m_f = \frac{1.9057}{0.87 \times 1000} = 2.1905 \times 10^{-3} m^3/hr$$

$$= 2.1905 \times 10^{-3} \times 1000 = 2.1905 \ litres/hr$$

$$ISFC = \frac{m_f}{IP} = \frac{1.9057}{6.67} = 0.2857 kg/kWhr$$

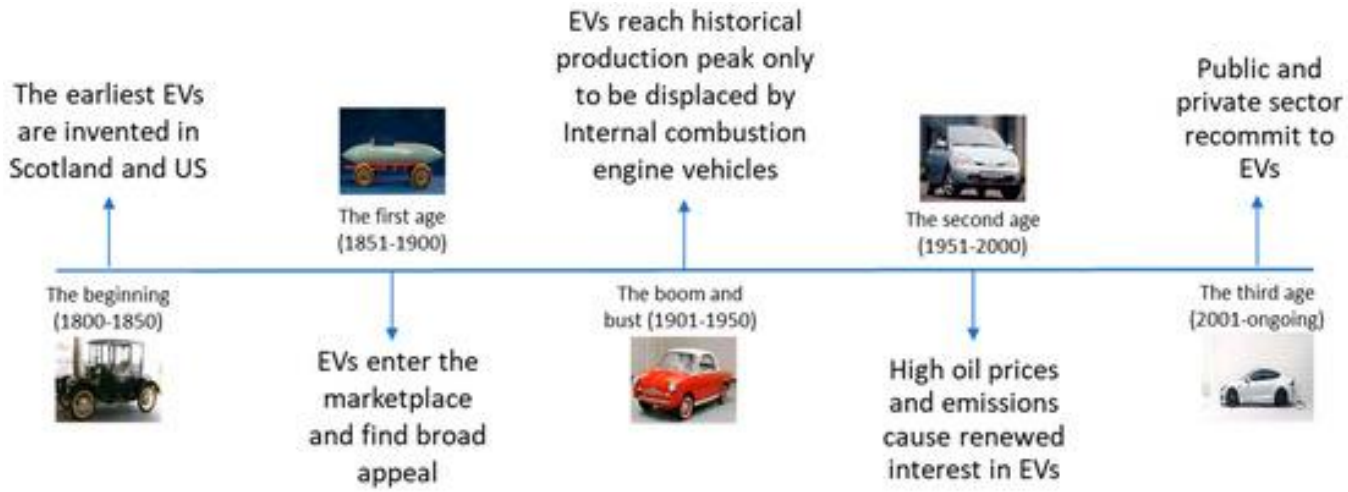
$$BSFC = \frac{m_f}{BP} = \frac{1.9057}{5} = 0.3811 kg/kWhr$$

INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

- The issues like global warming, depleting fossil fuel reserves, and greenhouse gas (GHG) emissions need dire attention for ensuring a sustainable future.

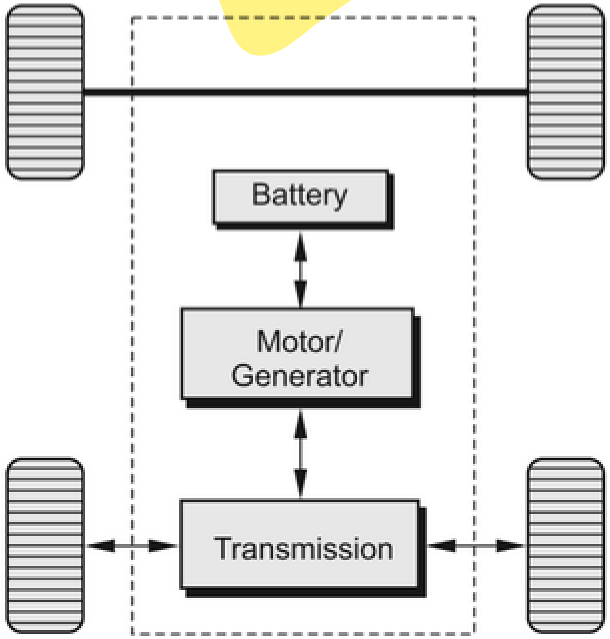
- Because the transportation sector is one of the largest contributors to the rising harmful emissions, the electrification of transportation is seen as a promising solution for this problem.

History of Electric Vehicles –



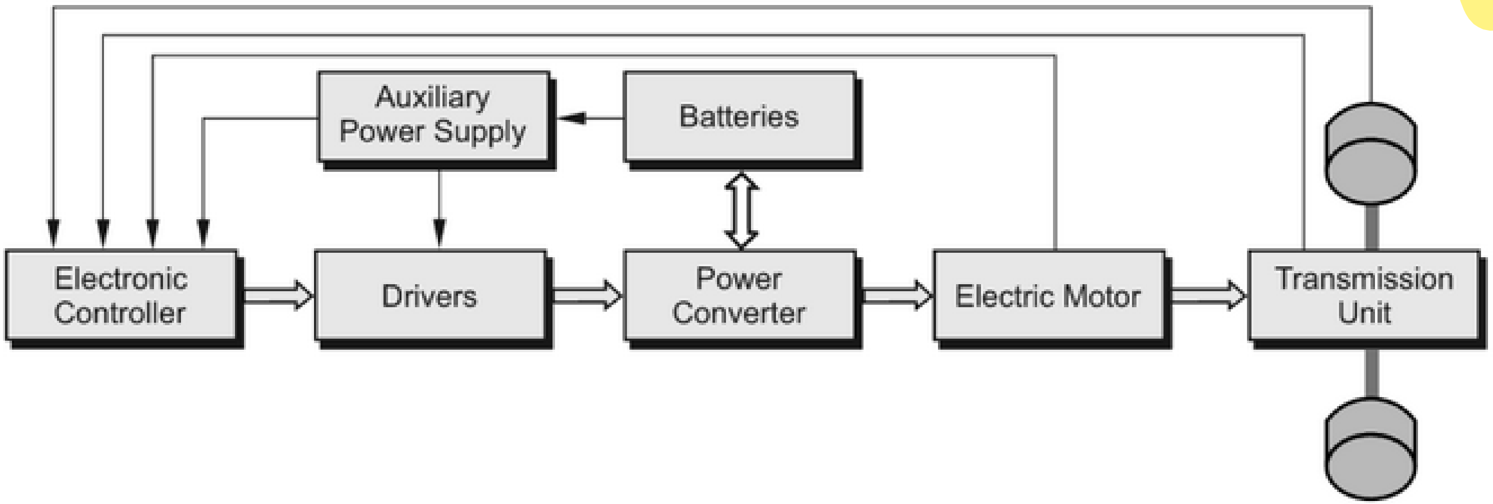
INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

- Electric vehicles are defined as vehicles which use an electric motor for propulsion.
- They are propelled by one or more electric motors, receiving power from an onboard source of electricity such as batteries, fuel cells, ultra capacitor, flywheel etc.
- EVs include a large range of vehicles from electric two wheelers, three wheelers (rickshaws), cars and electric buses and trucks.

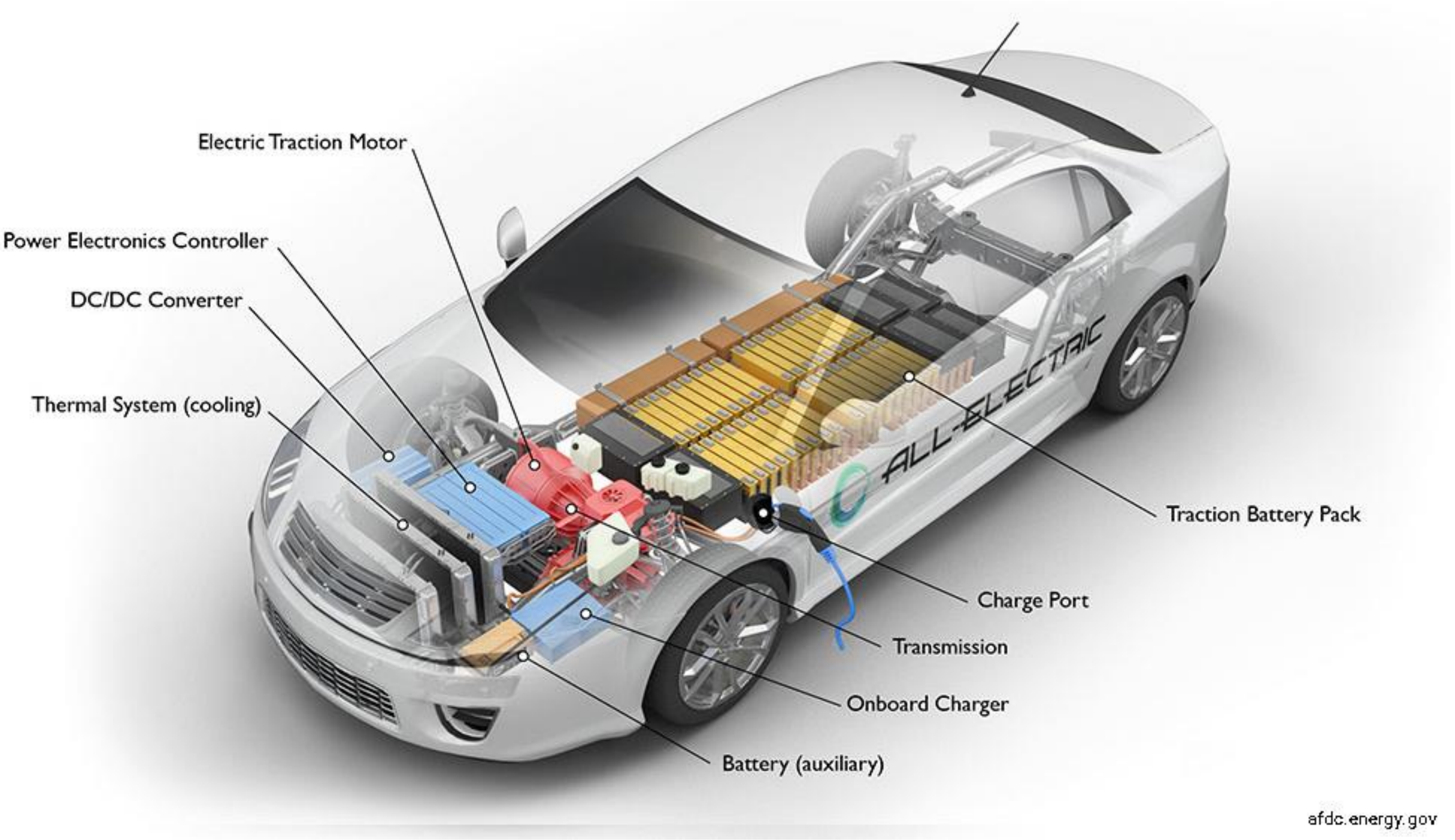


INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

Major Components of EV:



- An electric vehicle consists of a battery that provides energy, an electric motor that drives the wheels and a controller that regulates the energy flow to the motor. There are no gear box and clutch in these vehicles.


Electric Traction Motor
Power Electronics Controller
DC/DC Converter
Thermal System (cooling)
ALL-ELECTRIC
Traction Battery Pack
Charge Port
Transmission
Onboard Charger
Battery (auxiliary)
afdc.energy.gov

INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

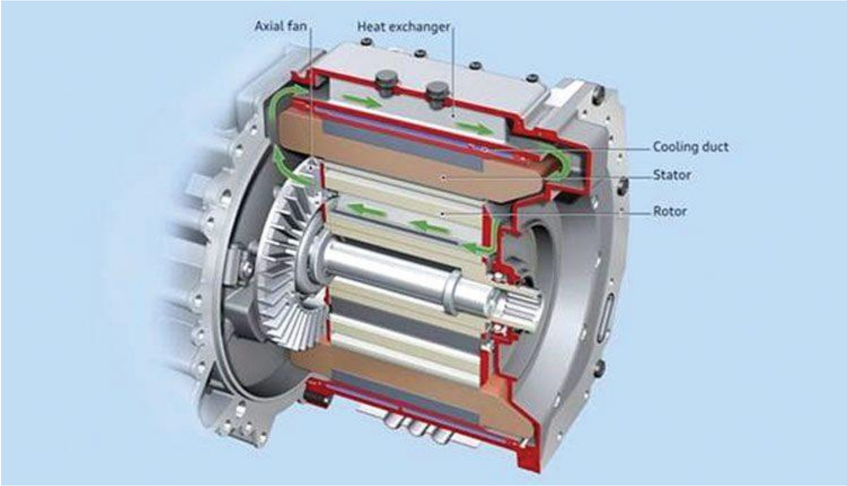
Major Components of EV:

Motor –

- The prime mover in electric vehicle is the high torque electric motor.

- It converts the energy stored in the power pack into mechanical motion. The power is directly delivered to the wheels or through the transaxle that propels the vehicle.

- While braking, it acts like a generator (regenerative braking) and recharges the batteries.



INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

Major Components of EV:

Power pack (Battery) –

- Automobile manufacturers use three types of rechargeable batteries. Those are lead acid batteries, nickel metal hydride (NiMH) batteries and lithium ion (Li – ion) batteries.

Charger –

- EVs have an on – board charger, which converts AC into DC power to charge the power pack.

Controller -

- EVs also have a computerized motor controller. This regulates the flow of energy from the power pack to the motor in direct relation to the pressure applied on the accelerator.

INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

Major Components of EV:

DC/DC converter –

- A 12V auxiliary battery is normally used in an electric car to power all 12V accessories such as lights, horn etc. EVs use a DC/DC converter which taps the full battery pack voltage and cuts it down to a regulated 13.5 V output similar to an alternator.

Energy Management System –

- The brain of EVs is the energy management system that monitors and controls all required functions.

- It is a computer based system that optimizes charging and energy output of batteries to maximize operating range and improve performance.

INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

Classification of EVs –

- There are 3 types of electric vehicle:

  i) Battery Electric Vehicle (BEV)

  ii) Hybrid Electric Vehicle (HEV)

  iii) Plug in Hybrid Electric Vehicle (PHEV)

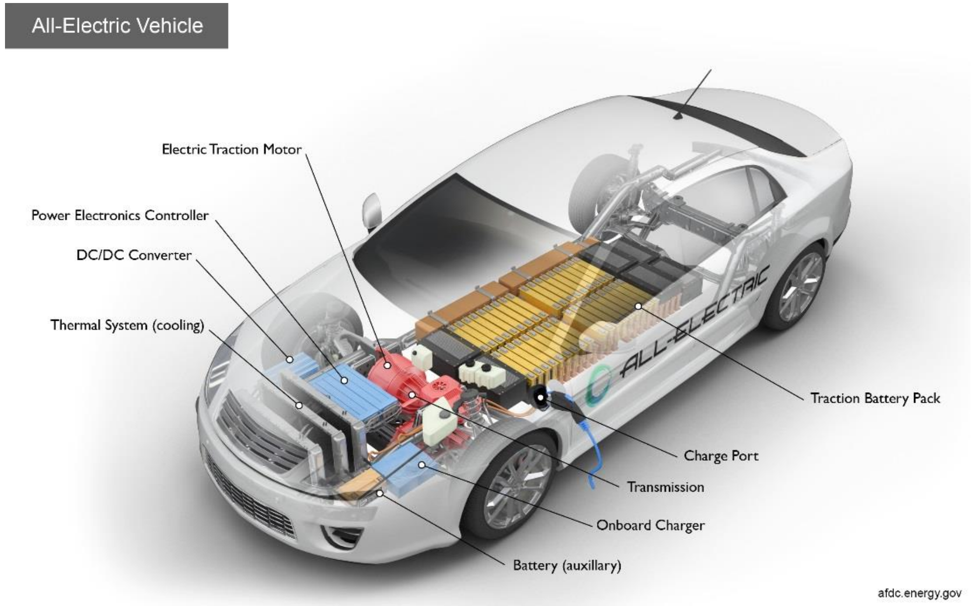
INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

Battery Electric Vehicle (BEV) –

- A battery electric vehicle (BEV) runs entirely using an electric motor and battery, without the support of a traditional internal combustion engine and must be plugged into an external source of electricity to recharge its battery.

- BEVs can also recharge their batteries through a process known as regenerative braking, which uses the vehicle's electric motor to assist in slowing the vehicle and to recover some of the energy normally converted to heat by the brakes.

- Examples – Tesla Model S Nissan Leaf, BMW i3, Mitsubishi iMi etc.



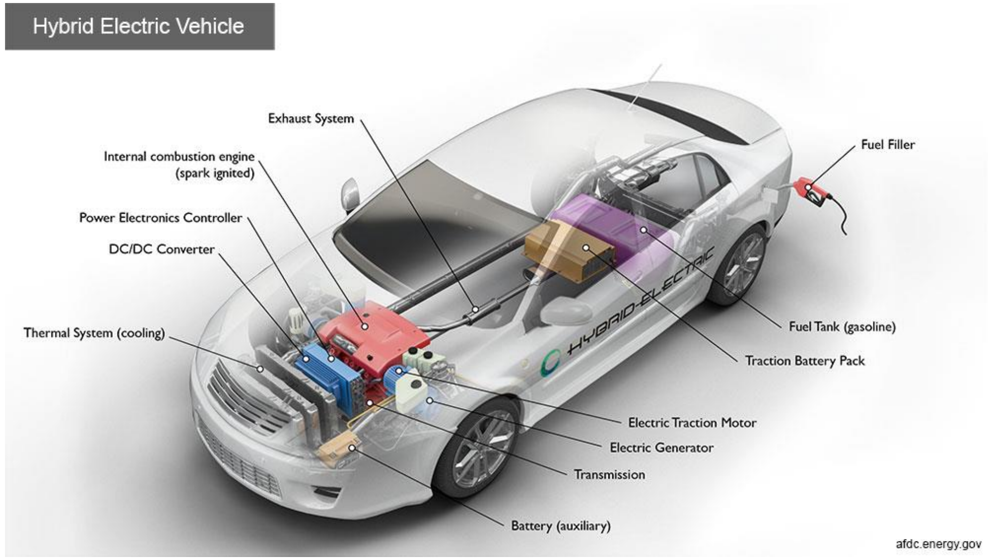
INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

Hybrid Electric Vehicle (HEV) –

- Hybrid electric vehicles have a supplemental fuel source to produce electricity on – board. They have two complementary drive systems: an IC engine with a fuel tank and an electric motor with a battery.

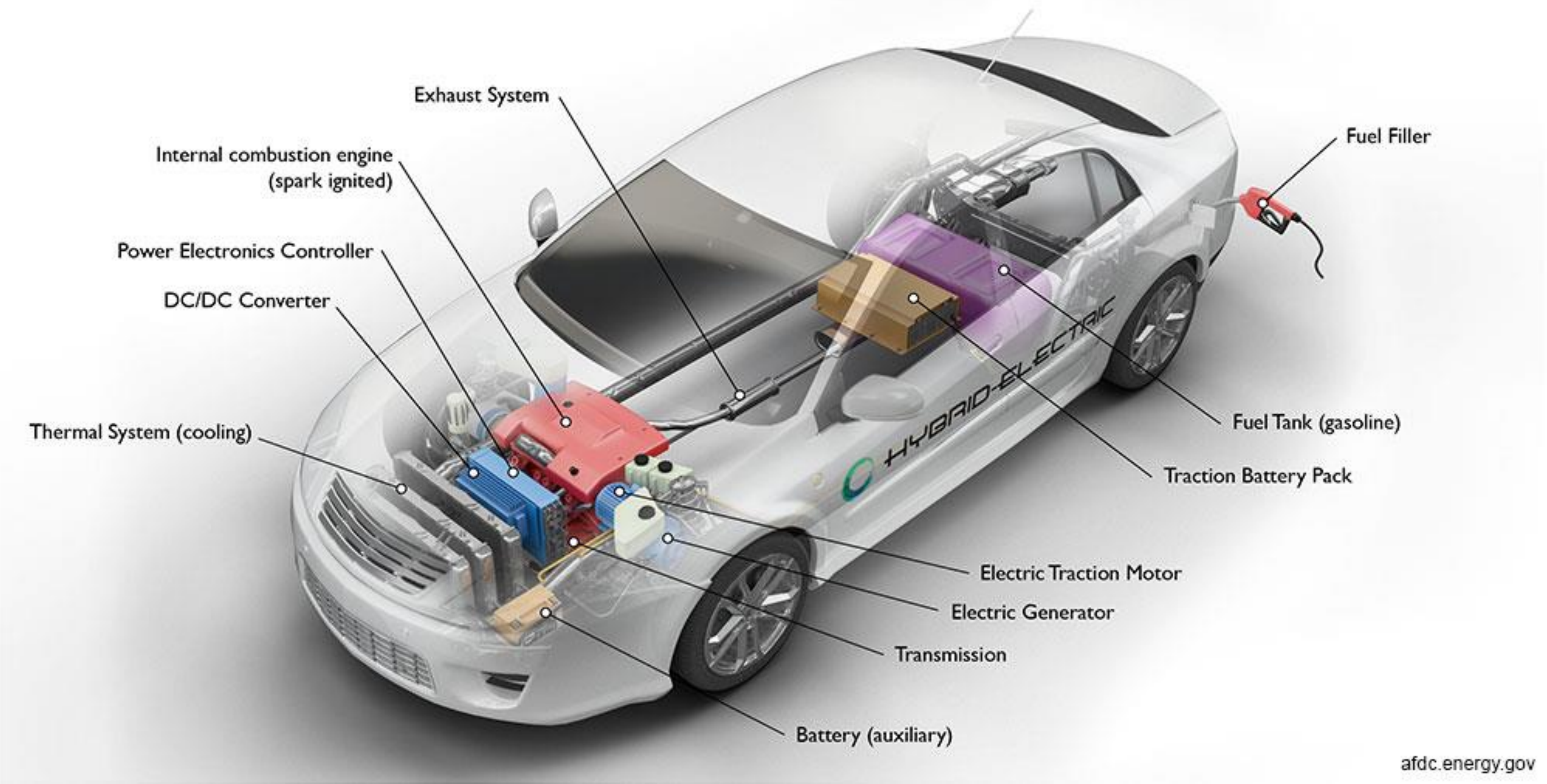
- Both the drive systems can be used to turn the transmission and the transmission then turns the wheels.

- HEVs cannot be recharged from the electricity grid – all their energy comes from fuel and from regenerative braking.



ELECTRIC AND HYBRID VEHICLES

Hybrid Electric Vehicle

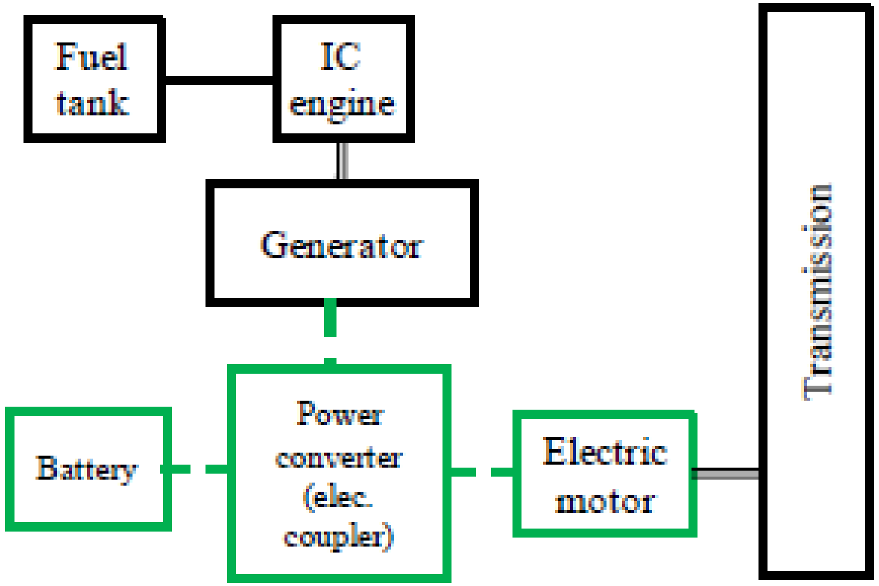


INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

Hybrid Electric Vehicle (HEV) – Architectures

i) Series Architecture

- In case of series hybrid system, the mechanical output is first converted into electricity using a generator.
- The converted electricity either charges the battery or can bypass the battery to propel the wheels via the motor and mechanical transmission.
- Conceptually, it is an ICE assisted Electric Vehicle (EV).



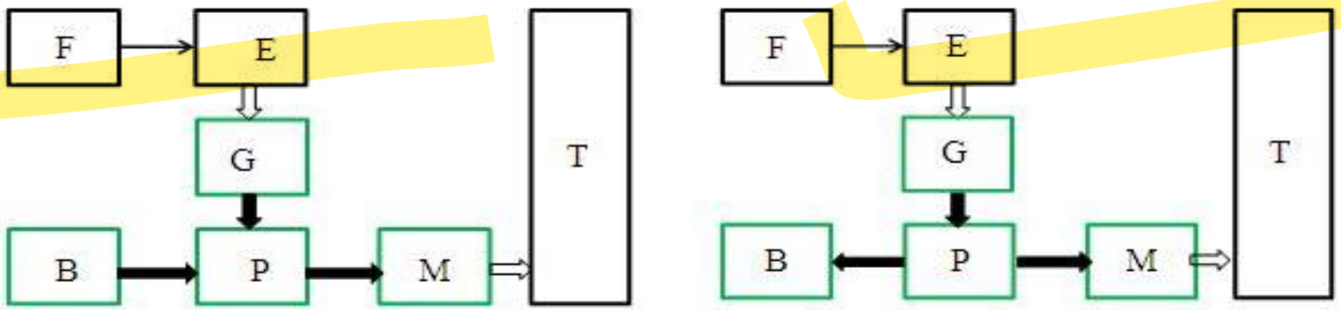


Figure 1a: Mode 1, normal driving or acceleration

Figure 1b: Mode 2, light load

Figure 1c: Mode 3, braking or deceleration

Figure 1d: Mode 4, vehicle at stop

B: Battery
E: ICE
F: Fuel tank
G: Generator
M: Motor
P: Power Converter

Electrical link
Hydraulic link
Mechanical link

T: Transmission (including brakes, clutches and gears)

INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

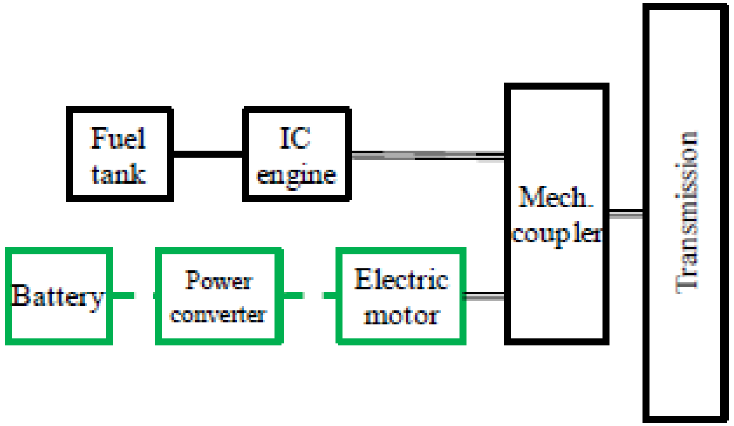
Hybrid Electric Vehicle (HEV) – Architectures

ii) Parallel Architecture

- The parallel HEV allows both ICE and electric motor (EM) to deliver power to drive the wheels.

- Since both the ICE and EM are coupled to the drive shaft of the wheels via two clutches, the propulsion power may be supplied by ICE alone, by EM only or by both ICE and EM.

- The EM can be used as a generator to charge the battery by regenerative braking or absorbing power from the ICE when its output is greater than that required to drive the wheels.



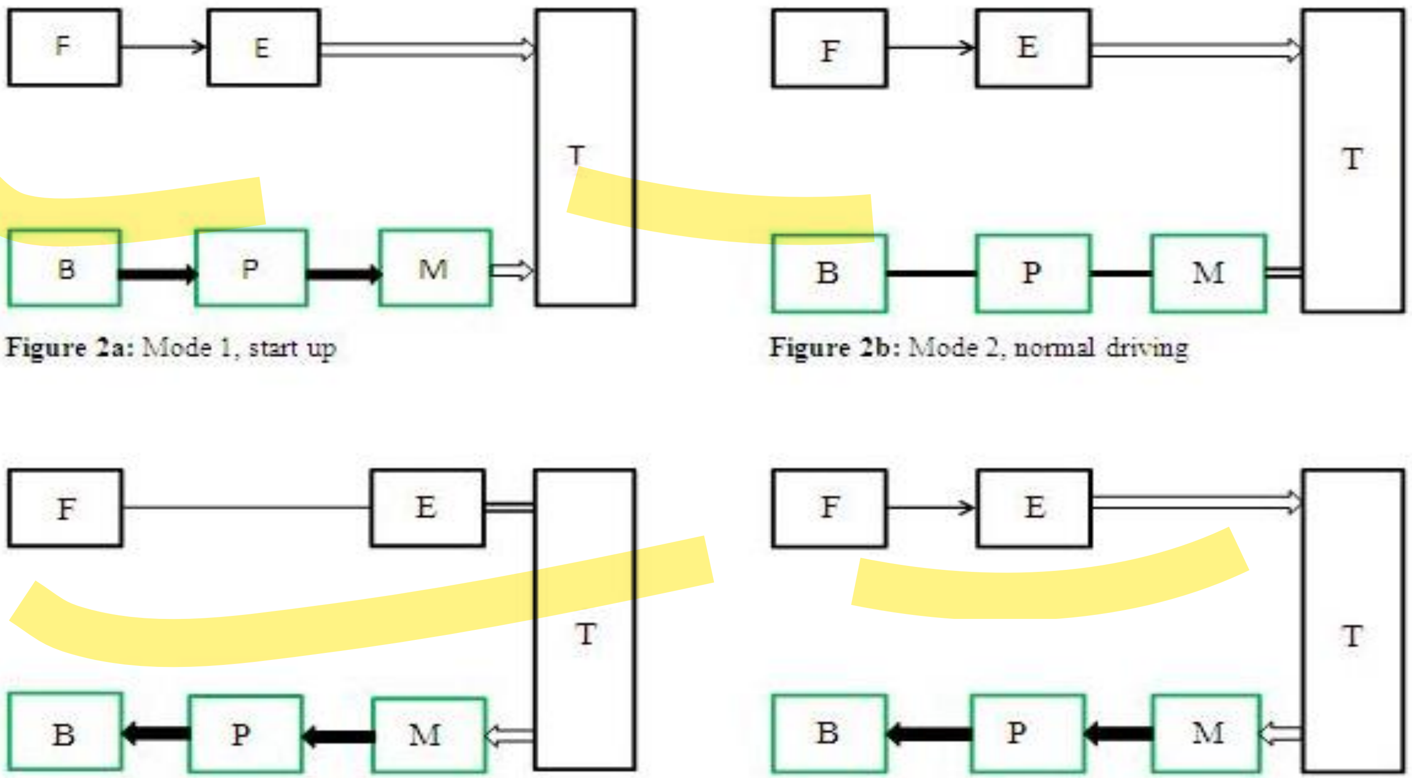


Figure 2a: Mode 1, start up

Figure 2b: Mode 2, normal driving

Figure 2c: Mode 3, braking or deceleration

Figure 2d: Mode 4, light load

B:Battery
E: ICE
F: Fuel tank
G: Generator
M: Motor
P: Power Converter

T: Transmission (including brakes, clutches and gears)

Electrical link
Hydraulic link
Mechanical link

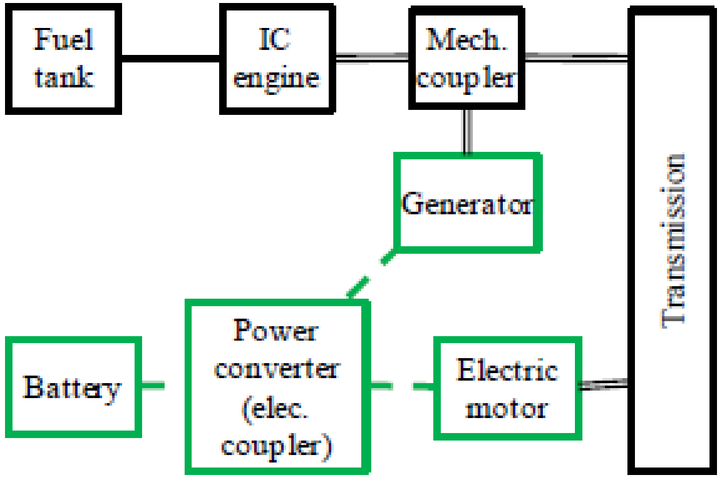
INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

Hybrid Electric Vehicle (HEV) – Architectures

iii) Series - Parallel Architecture

- In the series-parallel hybrid, the configuration incorporates the features of both the series and parallel HEVs.

- However, this configuration needs an additional electric machine and a planetary gear unit making the control complex.



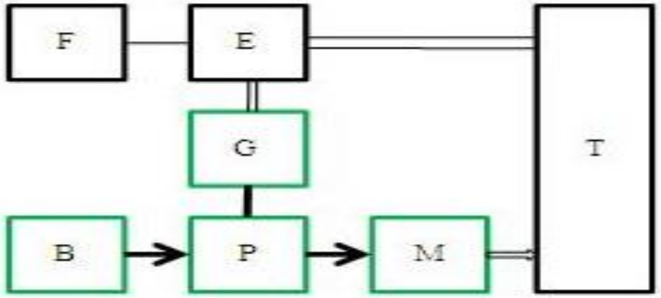


Figure 3a: Mode 1, start up

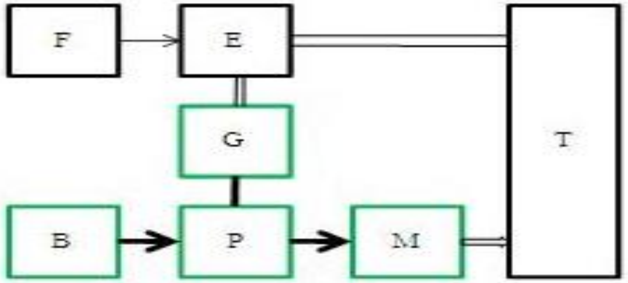


Figure 3b: Mode 2, acceleration

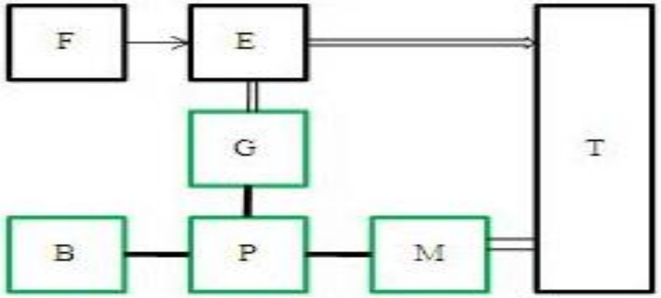


Figure 3c: Mode 3, normal drive

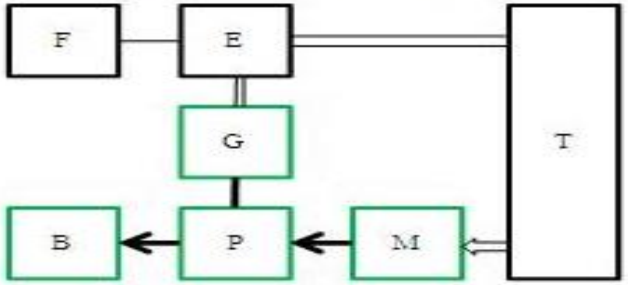


Figure 3d: Mode 4, braking or deceleration

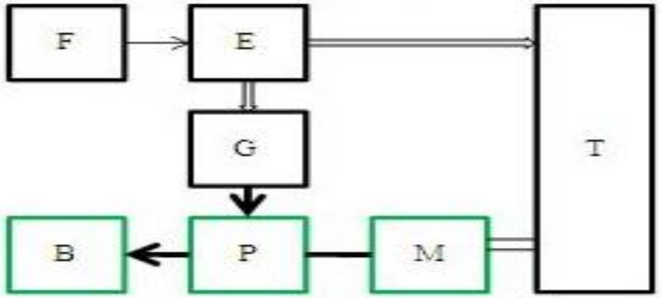


Figure 3e: Mode 5, battery charging during driving

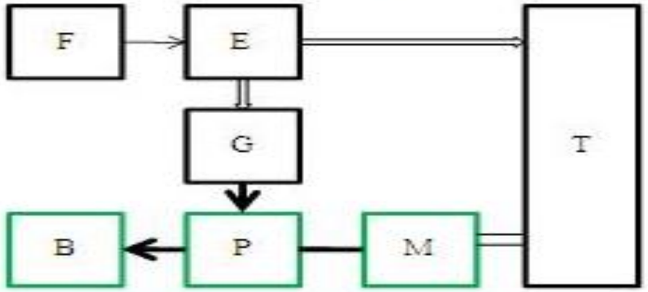


Figure 3f: Mode 6, battery charging during standstill

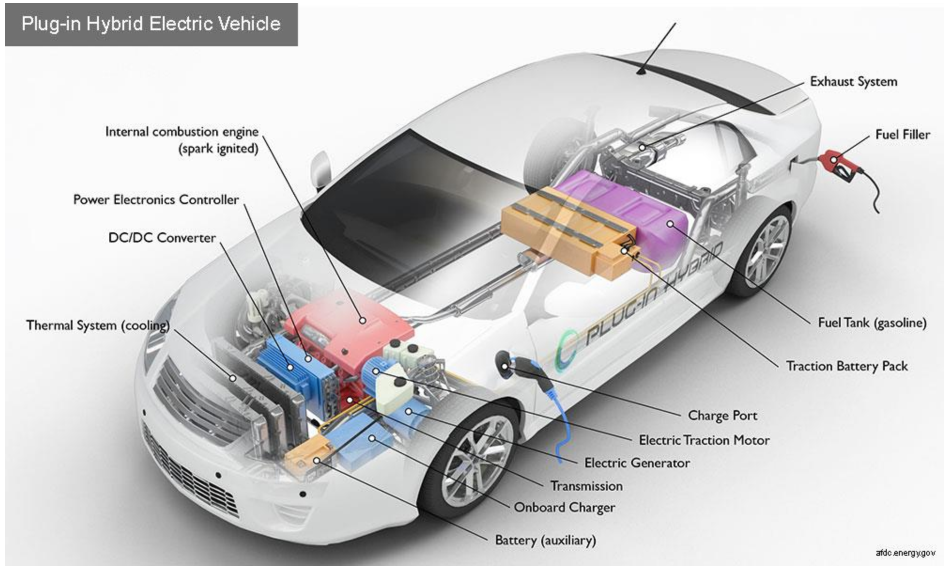
INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

Plug in Hybrid Electric Vehicle (PHEV) –

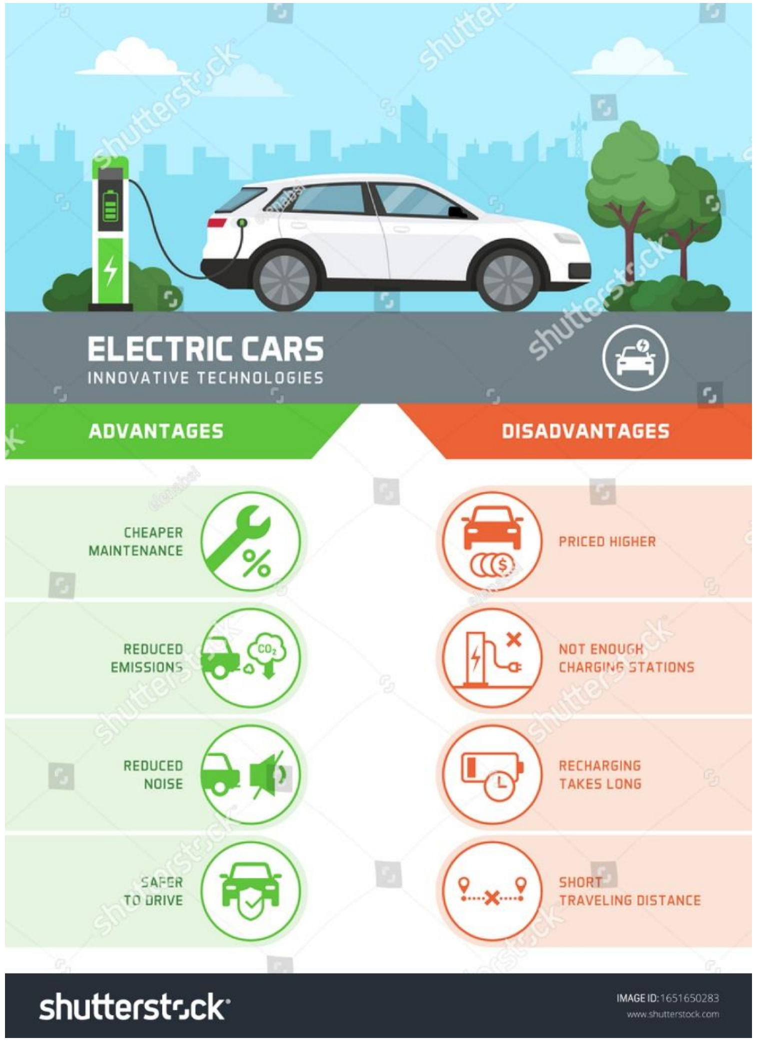
- Plug in hybrids use an electric motor and battery that can be plugged into the power grid to charge the battery, but also have the support of an internal combustion engine that may be used to recharge the vehicle's battery and/or to replace the electric motor when the battery is low.

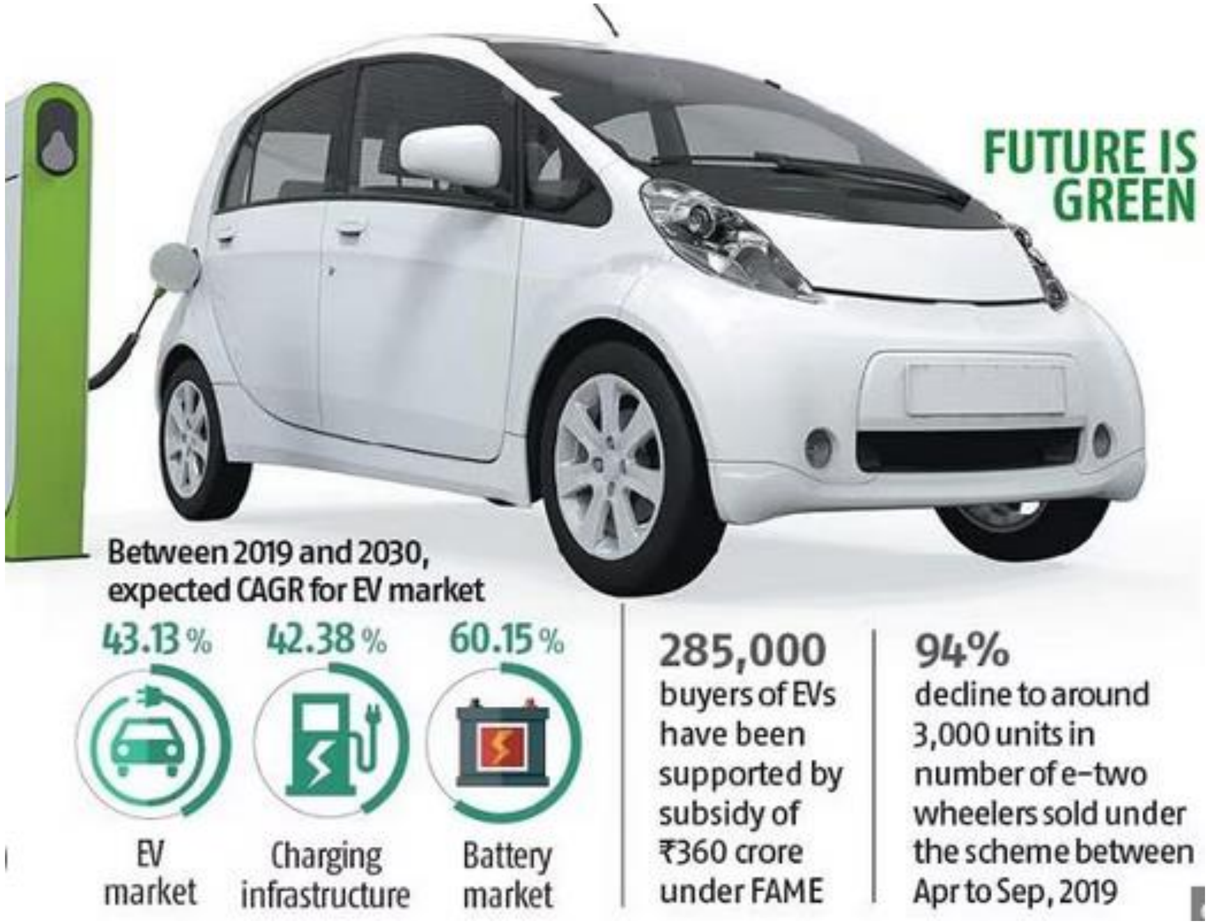
- Because Plug in hybrids use electricity from the power grid, they often realize more savings in fuel costs than tradition hybrid electric vehicles (HEV).

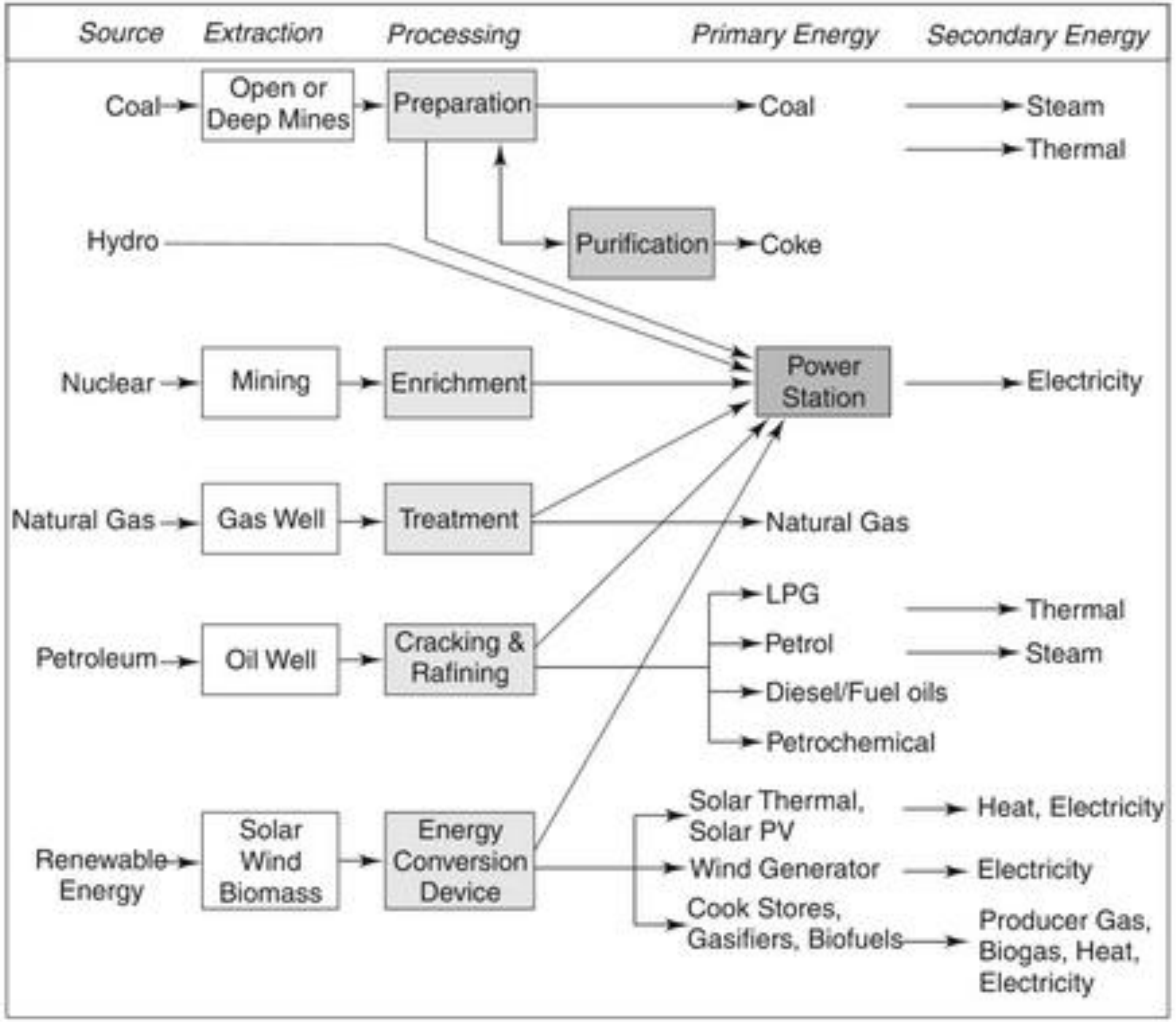
- Examples – Cadillac ELR, GM Chevy Volt, Toyota Prius Plugin etc.



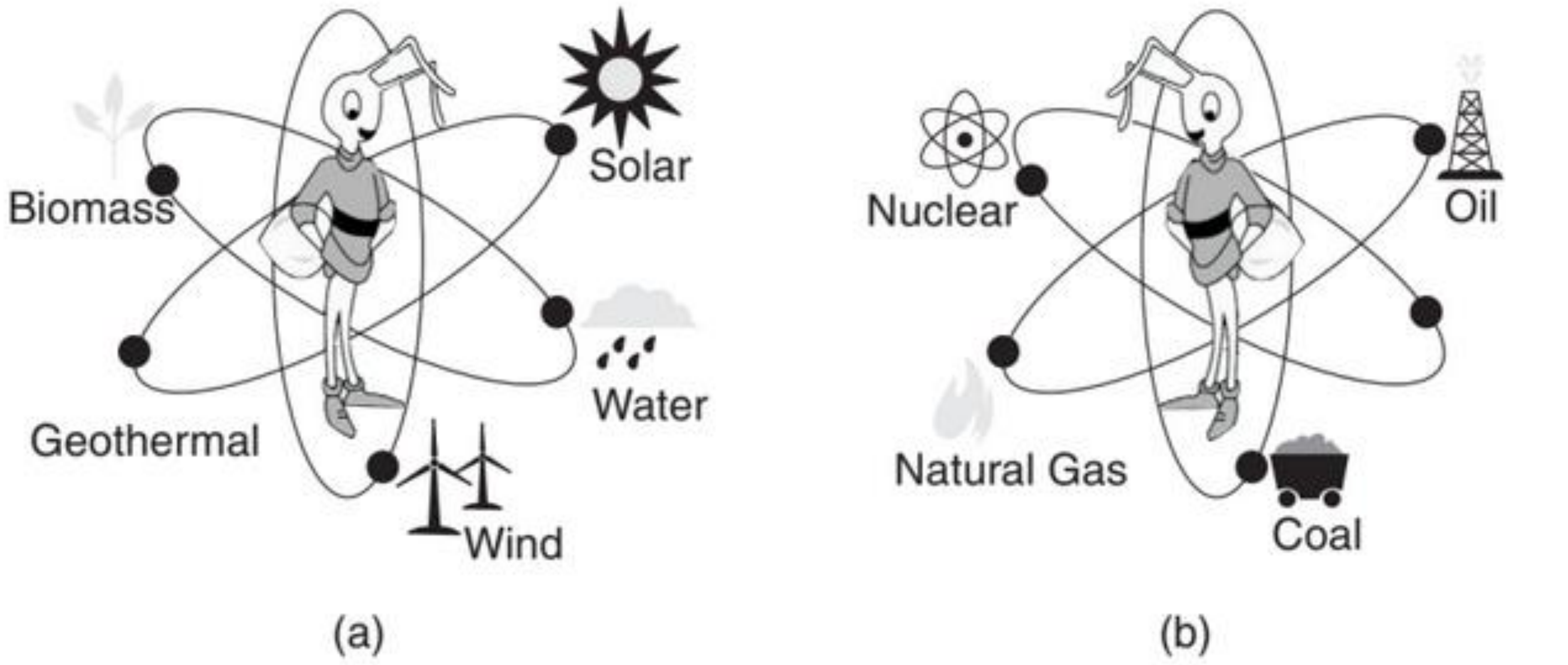
INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES







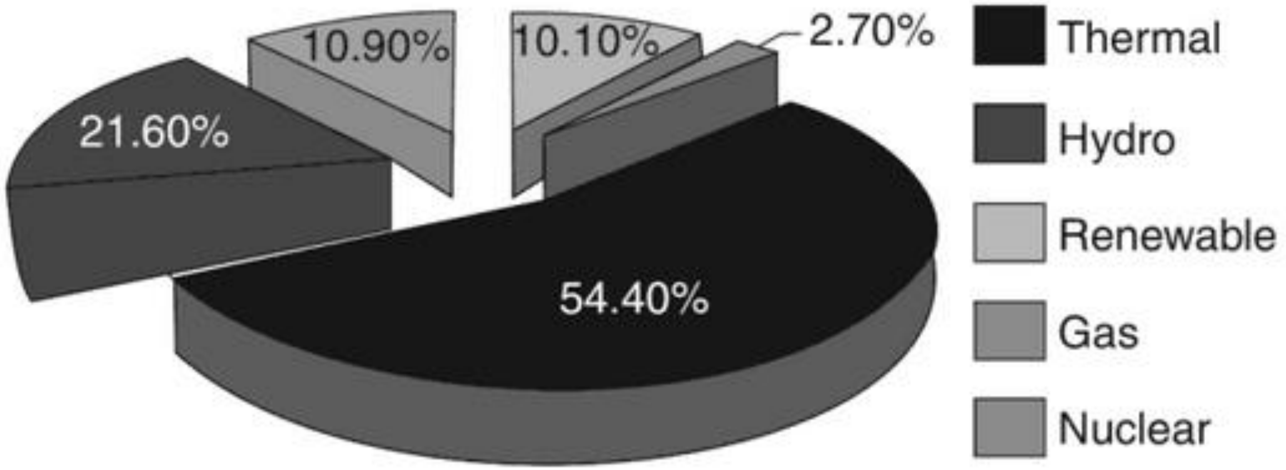
Major primary and secondary energy sources



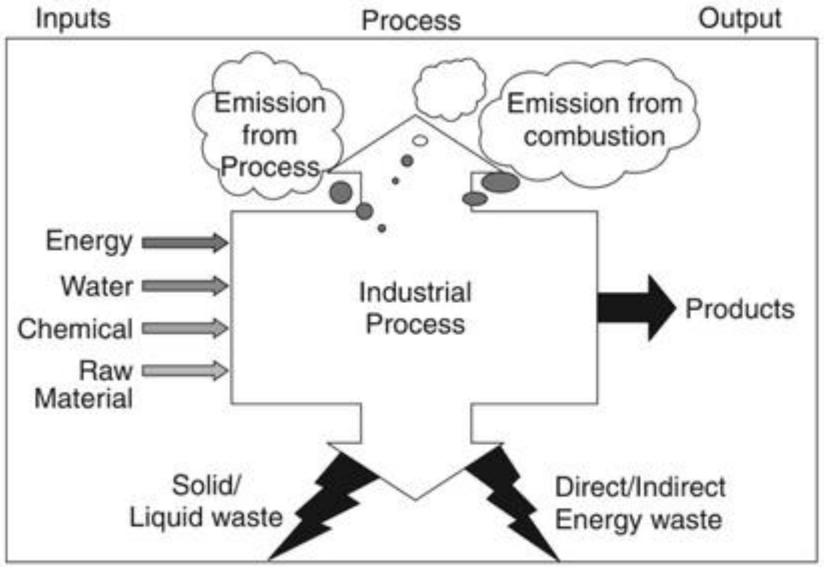
(a) Renewable and (b) Non-renewable energy sources

Given the limited amount of domestic resources of conventional energy, renewable energy resources have been an important component of India's energy planning process.

Technology	Capacity installed (MW)
Coal	11,202
Hydro	38,990
Renewable	27,300
Gas	18,381
Nuclear	4,780
Total	201,473



The use of fossil fuels by the industry (coal, oil and gas) leads to environment pollution by emitting oxides of sulphur (SO_x), nitrogen (NO_x), particulates and carbon mono-oxide. In addition, refrigerant systems use chlorofluorocarbons which on discharge or leakage deplete the ozone layer of the atmosphere. Very often, the industry discharges waste materials into water bodies or on earth resulting in water and groundwater contamination. Chemical and fertilizer industries release toxic gases, while cement and power plants spew particulates into the atmosphere. Typical inputs, outputs, and emissions for a typical industrial process are shown



NON CONVENTIONAL ENERGY SOURCES