Mechanical Engineering Science

Notes

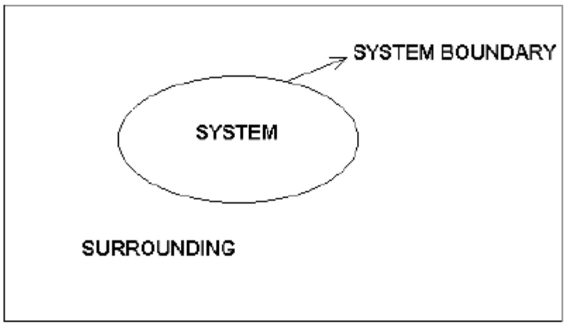
Unit: 1 – Principles of Thermodynamics, Fluid Energy, IC Engines and HEVs Dr. MBK

Introduction:

There are different forms of energy; all the energy cannot be used as a work. The convertibility of energy into work depends on its availability, i.e., how much energy can be converted into useful work. Thermodynamics is a branch of science and engineering that deals with interaction of energy mainly in the forms of heat and work. Thermodynamics is concerned with thermal behaviour of a matter and its interaction with other physical and chemical behaviour of the matter. Broadly, thermodynamics is studied in two forms—classical and statistical. Classical thermodynamics is concerned with the macrostructure of matter. It addresses the major characteristics of large aggregations of molecules and not the behaviour of individual molecules. The microstructure of matter is studied in kinetic theory and statistical mechanics. Statistical thermodynamics is concerned with the microstructure of the matter and addresses behaviour of individual molecules of the matter. In this chapter, only classical approach to thermodynamics has been discussed. Gases are very important part of engineering thermodynamics; therefore, to know the behaviour of ideal gas at standard temperature and pressure is very important. In this chapter, we have also discussed about the different gas laws and universal gas constants.

System: System is the fixed quantity of matter and/or the region that can be separated from everything else by a well-defined boundary/surface. Thermodynamic system is the system on which thermodynamic investigation is done. The surface separating the system and surroundings is known as the control surface or system boundary. The control surface may be movable or fixed. Everything beyond the system is the surroundings. A system of fixed mass is referred to as a closed system. When there is flow of mass through the control surface, the system is called an open system. An isolated system is a closed system that does not interact in any way with its surroundings.

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



In thermodynamics, systems are classified based on their interaction with the surroundings: an open system can exchange both matter and energy (heat or work) with its environment, like a boiling pot without a lid where steam escapes; a closed system can exchange energy but not matter, such as a sealed pressure cooker that allows heat transfer but keeps the contents inside; and an isolated system cannot exchange either matter or energy with its surroundings, idealized by a perfectly insulated thermos flask that prevents heat loss and mass transfer.

Macroscopic Study in Thermodynamics

- Macroscopic means looking at the system as a whole, without focusing on individual particles (atoms or molecules).
- It deals with bulk properties like pressure, temperature, volume, internal energy, and entropy.
- These properties are averages that describe the overall state of the system.
- Macroscopic thermodynamics is based on measurable quantities and uses laws of thermodynamics.
- Example: Measuring the temperature and pressure of a gas in a cylinder without considering the behavior of each molecule.

Microscopic Study in Thermodynamics

- Microscopic looks at the system at the level of individual particles — atoms, molecules, or ions.
- It focuses on molecular motion, collisions, and interactions.
- This approach is the basis of statistical mechanics, which connects microscopic behavior to macroscopic properties.
- It helps explain why macroscopic properties behave the way they do, based on the collective behavior of many particles.
- Example: Analyzing how gas molecules move and collide to understand pressure and temperature.

State: At any instant of time, the condition of a system is called state. The state at a given instant of time is defined by the properties of the system such as pressure, volume, temperature, etc. A property is any quantity whose numerical value depends on the state but not on the history of the system.
There are two types of properties—extensive and intensive. Extensive properties depend on the size or extent of the system. Volume, mass, energy, and entropy are examples of extensive properties. An extensive property is additive in the sense that its value for the whole system equals the sum of the values for its molecules. Intensive properties are independent of the size or extent of the system. Pressure and temperature are examples of intensive properties.

Process: Two states are identical if, and only if, the properties of the two states are same. When any property of a system changes in value there is a change in state, and the system is said to undergo a *process*. When a system from a given initial state goes into a sequence of processes and finally returns to its initial state, it is said to have undergone a *cycle*.

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.

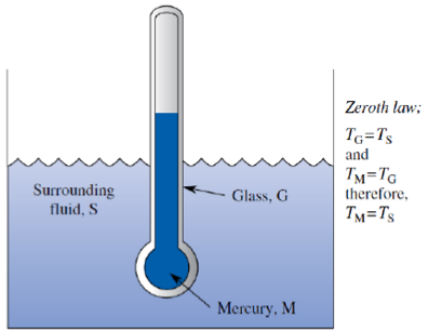
Equilibrium: In thermodynamics the concept of equilibrium includes not only a balance of forces, but also a balance of other influencing factors, such as thermal equilibrium, pressure equilibrium, phase equilibrium, etc. To observe a thermodynamic equilibrium in a system, one may test it by isolation of the system from its surroundings and watch for changes in its observable properties. If no change takes place, it may be said that the system is in equilibrium. The system can be at an equilibrium state. When a system is isolated, it cannot interact with its surroundings; however, its state can change as a consequence of spontaneous changes occurring internally as its intensive properties, such as temperature and pressure, tend toward uniform values. When all such changes cease, the system is in equilibrium. At equilibrium, temperature and pressure are uniform throughout. If gravity is significant, a pressure variation with height can exist, as in a vertical column of liquid.

Zeroth law of thermodynamics is law of thermal equilibrium, which states that if a system A is in thermal equilibrium with systems B and C, then systems B and C will be in thermal equilibrium as well.

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.



Equality of temperature:
When two objects are in contact, heat flows from the hotter object to the cooler one.
This heat flow continues until both objects reach the **same temperature**.
At that point, **no net heat transfer** occurs between them.
This state is called **thermal equilibrium**.

Example

- If you put a hot cup of tea and a cold room-temperature spoon together, heat will flow from the tea to the spoon.
- Eventually, the spoon warms up, and the tea cools down.
- They both reach the **same temperature** (equality of temperature), and then heat flow stops.

Quasi-static Process

A **quasi-static process** (or **quasi-equilibrium process**) is a thermodynamic process that happens **infinitely slowly**, so the system remains nearly in **thermodynamic equilibrium** at every instant during the process.

Key Features

- The process proceeds so slowly that the system passes through a continuous sequence of **equilibrium states**.
- Because the system is always nearly at equilibrium, its properties (like pressure, volume, temperature) are well-defined at every moment.
- This makes quasi-static processes idealized models — real processes can never be perfectly quasi-static because they always involve some finite rate and irreversibility.

Why is it Important?

- It allows us to apply the laws of thermodynamics easily because the system is always close to equilibrium.
- Many thermodynamic equations and calculations assume quasi-static processes for simplicity and accuracy.

- Reversible processes are a subset of quasi-static processes where there is no entropy generation or energy loss.

Example
- Slowly compressing a gas in a piston so that the gas pressure and temperature adjust at every small step, staying almost uniform inside.
- If you compress too fast, pressure and temperature gradients develop, and the process is no longer quasi-static.

Internal Energy: The Internal Energy (U) of a system is the total energy content of the system. It is the sum of the kinetic, potential, chemical, electrical, and all other forms of energy possessed by the atoms and molecules of the system. The Internal Energy (U) is path independent and depends only on temperature for an ideal gas. Internal energy may be stored in the system in following forms:
_ Kinetic energy of molecules
_ Molecular vibrations and rotations
_ Chemical bonds that can be released during chemical reaction
_ Potential energy of the constituents of the system
Work: Work in thermodynamics may be defined as any quantity of energy that flows across the boundary between the system and surroundings which can be used to change the height of a mass in the surroundings.
Heat: Heat is defined as the quantity of energy that flows across the boundary between the system and surroundings because of a temperature difference between system and surroundings. The characteristics of heat are as follows:
_ Heat is transitory and appears during a change in state of the system and surroundings. It is not a point function.
_ The net effect of heat is to change the internal energy of the system and surroundings in accordance to first law.
_ If heat is transferred to the system, it is positive and if it is transferred from the system it is negative.
Energy Transfer Across the System Boundary (Heat and Work)
Energy transfer across the boundary of a closed system may occur in the form of heat and work. When a closed system is left in a medium of different temperature, energy transfer takes place between the system and the surrounding until thermal equilibrium is reached. The direction of energy transfer is always from the higher temperature side to the lower temperature side. Once the temperature equilibrium is established, energy transfer stops. In the processes described earlier, energy is said to be transferred in the form of heat. Heat is defined as the form of energy that is transferred between two systems or between a system and its surroundings by virtue of a temperature difference.
During adiabatic process heat transfer is negligible. A process can be adiabatic when either the system is well insulated so that only a negligible amount of heat can pass through the boundary or both the system and the surroundings are at the same temperature. Even though there is no heat transfer during an adiabatic process, the energy content, and thus the temperature of a

system can still be changed by other means such as work, i.e., the heat can be transformed into work. If the energy crossing the boundary of a closed system is not heat, it must be work. Heat is easy to recognize as its driving force is a temperature difference between the system and its surroundings. Then we can simply say that an energy interaction that is not caused by a temperature difference between a system and its surroundings is work.

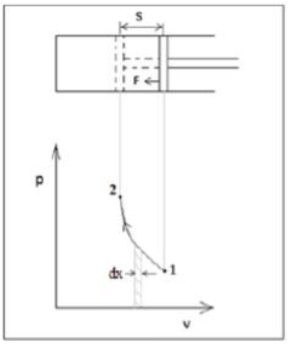
Sign Conventions for Heat and Work Interaction Heat and work are directional quantities, and thus the complete description of a heat or work interaction requires the specification of both the magnitude and direction. One way of doing that is to adopt a sign convention. The generally accepted formal sign convention for heat and work interactions is as follows:

- Heat transfer to a system and work done by a system are positive.
- Heat transfer from a system and work done on a system are negative.

Similarity Between Heat and Work

Heat and work are energy transfer mechanisms between a system and its surroundings. Some of the similarities between heat and work are as follows:

- Heat and work are boundary phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a process, not a state.
- Both are path functions.



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.

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: -

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

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

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.

<u>For an Isothermal Process</u>

We have $P_1V_1 = P_2V_2 = PV$ = Constant

Hence P = Constant/V

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

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

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

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

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

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 = 0 $P_1/P_2 = T_1/T_2$ (Kelvin)	W = 0
5	Isobaric process	P = constant. dP = 0 $V_1/T_1 = V_2/T_2$	$W = P(V_2 - V_1)$

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

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/ m^3, determine the work done by the system.

Important Observations

Process is isothermal since PV=constant

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

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

Data provided

$m = 1.5$ kg; $p_1 = 0.1$ MPa;

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

Solution

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

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

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

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

A mass of gas is compressed in a quasi static process from 80 kPa, 0.1 m^3 to 0.4MPa , 0.03 m^3. Assuming the P & V are related by up PV^n = constant, determine the work done by the system.

Important Observations

Process is polytropic → PV^n = constant

Data provided

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

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

Solution

1. Determination of polytropic index n

$p_1 V_1^n = p_2 V_2^n$

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

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**

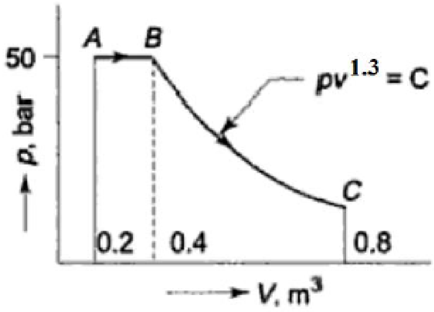
2. Determination of work done

$$W_{1-2} = \frac{p_1 V_1 - p_2 V_2}{n - 1} \text{ for a polytropic process}$$

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

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

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

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

1 bar = 100 kPa

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

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

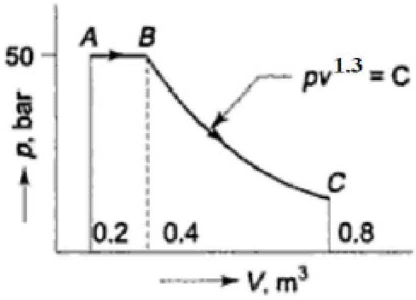
Solution

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

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

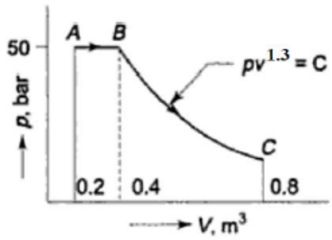
$$\mathbf{W_{A-B} = 1000\ kJ}$$

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

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

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

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

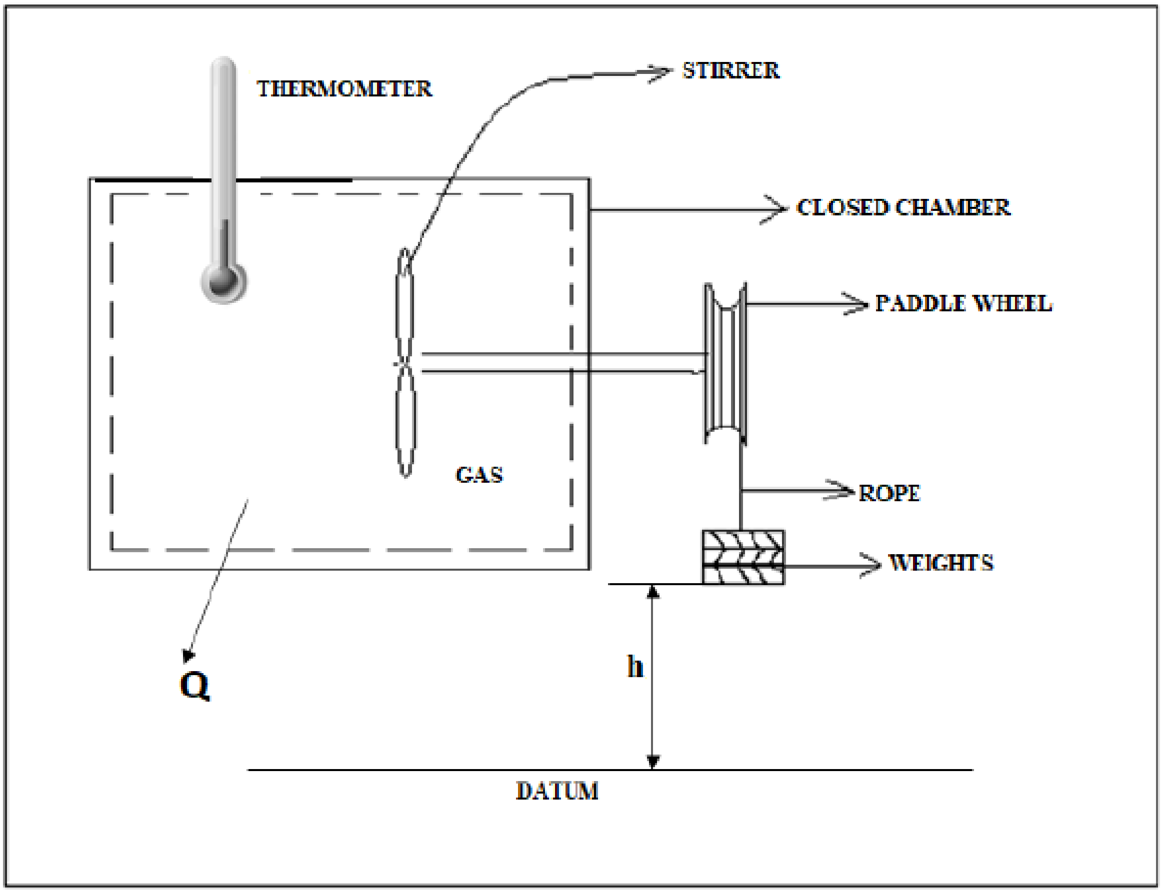


First Law of Thermodynamics – Joule's Experiment

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.



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.

'***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

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

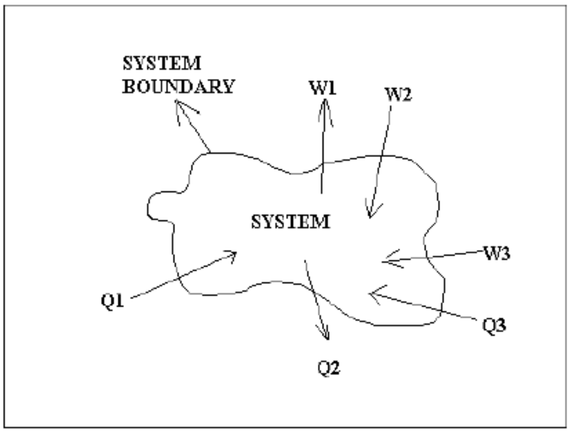
$$\sum_{\text{cycle}} W = J \sum_{\text{cycle}} Q,$$

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



Consider the system shown.

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

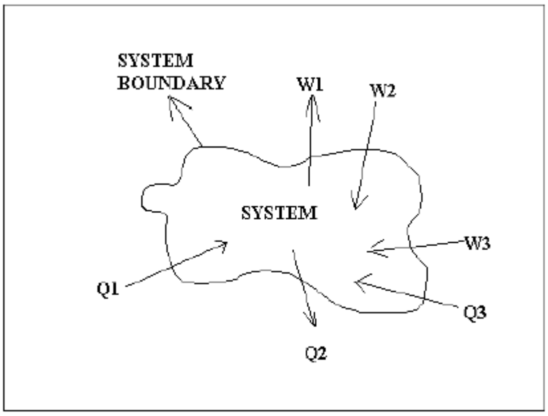
By law of conservation of energy

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

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



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

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

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

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

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

$$\int_1^2 \partial \mathrm{Q} = \int_1^2 \mathrm{dE} + \int_1^2 \partial \mathrm{W}$$

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

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

First Law for a Closed System Undergoing a Cyclic Process

In a **cyclic process**, the system returns to its **initial state** at the end of the cycle.

Since the internal energy U is a state function, **change in internal energy over one complete cycle is zero**:

$$\Delta U = 0$$

So, the first law simplifies to:

$$Q = W$$

Meaning, **the net heat added to the system equals the net work done by the system** during the cycle.

First Law for a Closed System Undergoing a Non-Cyclic Process

In a **non-cyclic process**, the system changes from one state to another, so the internal energy changes:

$$\Delta U = U_2 - U_1 \neq 0$$

The first law is written as:

$$\Delta U = Q - W$$

Here, Q is the net heat added to the system and W is the work done by the system.

This means the change in internal energy equals the net energy added as heat minus the work done by the system.

Process Type	Internal Energy Change ΔU	First Law Form
Cyclic process	0	$Q = W$
Non-cyclic process	Not zero	$\Delta U = Q - W$

Internal Energy: The Internal Energy (U) of a system is the total energy content of the system. It is the sum of the kinetic, potential, chemical, electrical, and all other forms of energy possessed by the atoms and molecules of the system. The Internal Energy (U) is path independent and depends only on temperature for an ideal gas. Internal energy may be stored in the system in following forms:

_ Kinetic energy of molecules

_ Molecular vibrations and rotations

_ Chemical bonds that can be released during chemical reaction

_ Potential energy of the constituents of the system

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

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

Solution

Process a–b

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

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

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

Process c–d

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

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

$W_{c\text{-}d} = 34{,}500$ **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			59,770

Process b–c

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

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

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

$\Sigma\, \Delta E = 0$

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

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

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

$\Sigma Q = -170$ 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

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

$\Delta E = 56.25$ kJ

$Q = \Delta E + W$

$0 = \Delta E + W$

$W = -\Delta E$

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

Limitations of the First Law of Thermodynamics

1. **Does Not Indicate Direction of Processes:**
   The first law states that energy is conserved, but it doesn't tell us which way a process will naturally occur. For example, it doesn't explain why heat flows from hot to cold, not the other way around.

2. **No Information About Spontaneity or Feasibility:**
   It can't predict whether a process is spontaneous or possible. A process might satisfy energy conservation but still never occur naturally.

3. **Ignores Entropy and Irreversibility:**
   The first law does not address the increase of entropy or the irreversibility of real processes, which are covered by the Second Law of Thermodynamics.

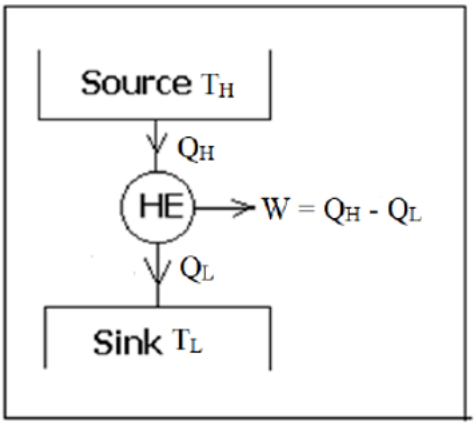
4. **Does Not Quantify Efficiency Limits:**
   While it ensures energy balance, it cannot determine the maximum efficiency of devices like heat engines — that's the domain of the Second Law.

Thermal Reservoir: A thermal reservoir is an idealized body or system that can absorb or supply unlimited amounts of heat without undergoing any change in its own temperature. It remains at a constant temperature throughout the heat exchange process.

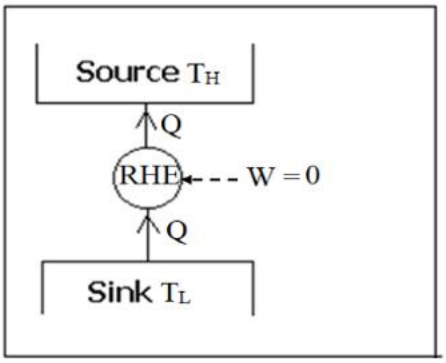
Heat Source: A heat source is a system or body that supplies heat energy to another system. It typically has a higher temperature than the system it transfers heat to.

Heat Sink: A heat sink is a system or body that absorbs or receives heat energy from another system. It usually has a lower temperature than the system losing heat.

Heat Engine: A heat engine is a device that converts heat energy into mechanical work by operating between a high-temperature heat source and a low-temperature heat sink. It absorbs heat from the source, partially converts this heat into work, and rejects the remaining heat to the sink.



Reversed Heat Engine: A reversed heat engine is a device that consumes mechanical work to transfer heat from a low-temperature reservoir to a high-temperature reservoir. Essentially, it works opposite to a heat engine, moving heat against the natural flow, and is used in devices like refrigerators and heat pumps.



The Second Law of Thermodynamics

Second law of thermodynamics overcomes the limitations of first law of thermodynamics. First law of thermodynamics does not tell how much of heat is changed into work. Second law of thermodynamics shows that the total heat supplied to a system cannot be transferred solely into the work using single reservoir, i.e., some part of heat must be rejected to sink. It also shows the direction of the energy transfer, i.e., heat cannot be transferred from lower temperature reservoir to higher temperature reservoir without external work done on the system.

Kelvin–Planck Statement

The Kelvin–Plank statement of the second law of thermodynamics refers to a thermal reservoir.

It is impossible to construct a heat engine that operates in a cycle and produces no other effect than the absorption of heat from a single thermal reservoir and the performance of an equivalent amount of work.

In Figure 1.11, it is shown that there are two reservoirs from which heat is interacted to do a work *W*net. Heat, *Q*H is taken from higher temperature reservoir and work is done and rest amount of heat is rejected to lower temperature reservoir. Thus, the total conversion of heat to work is impossible; there will always be rejection of some part of the heat supplied by the heat engine.

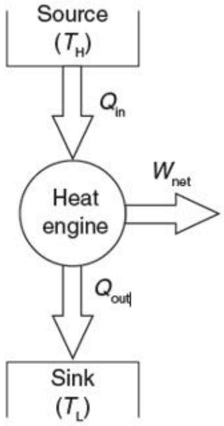
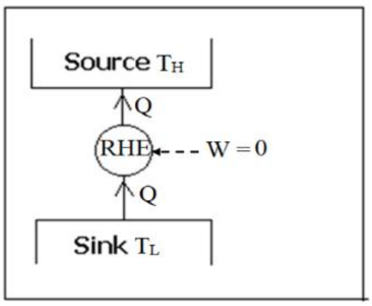


Figure a Heat Engine

Clausius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower temperature body to higher temperature body. In other words, a refrigerator cannot be operated without external work supplied to refrigeration system. Heat flows from high temperature to low temperature reservoir. To reverse the direction of flow of heat, there is requirement of some additional work on the system. On this principle refrigerator and heat pump are working.



Fluid Enenergy

Hydraulic machines are the devices that convert hydraulic energy into mechanical energy or mechanical energy into hydraulic energy. Hydraulic turbines are the basic prime movers which convert the hydraulic energy (in the form of pressure/kinetic energy) into mechanical energy. Pressure energy is developed due to head of water in the form of potential energy and kinetic energy is developed due to mass flow of water with some velocity. The shaft of hydraulic turbine rotates due to impact/ reaction force of water on hydraulic blades; the shaft of the turbine is coupled with generator which produces electrical energy. Pump converts mechanical energy into hydraulic energy (pressure energy).

Fluid energy (like the energy in moving water, steam, or air) can be converted into mechanical energy through devices called **turbines** or **impellers**. This process harnesses the **kinetic energy** (energy of motion) and/or **pressure energy** of the fluid and transforms it into useful mechanical work, such as rotating a shaft.

Examples:

Hydroelectric turbines: Convert energy from flowing water into mechanical rotation that generates electricity.

Steam turbines: Convert energy from high-pressure steam into mechanical work.

Wind turbines: Convert kinetic energy of wind into mechanical rotation.

- 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.

- 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

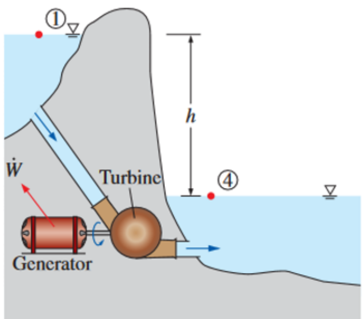
$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

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

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

- 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 $W_{max} = \dot{m}\Delta e_{mech}$



$\dot{W}_{\text{max}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}g(z_1 - z_4) = \dot{m}gh$
since $P_1 \approx P_4 = P_{\text{atm}}$ and $V_1 = V_4 \approx 0$

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

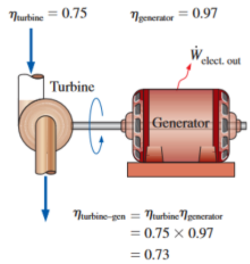
$$\eta_{\text{pump}} = \frac{\text{Mechanical power increase of the fluid}}{\text{Mechanical power input}} = \frac{\Delta \dot{E}_{\text{mech, fluid}}}{\dot{W}_{\text{shaft, in}}} = \frac{\dot{W}_{\text{pump, }u}}{\dot{W}_{\text{pump}}}$$

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

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

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

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

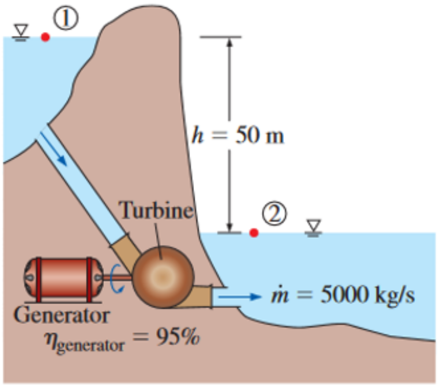
Generator: $$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect, out}}}{\dot{W}_{\text{shaft, in}}}$$

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

IC Engines:

- **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.

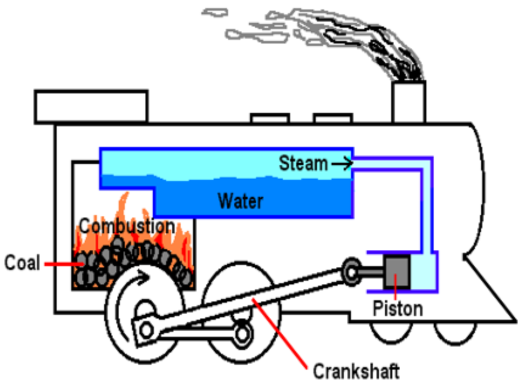
- Heat engines can be broadly classified into two categories:

(i) Internal Combustion Engines (IC Engines)

(ii) External Combustion Engines (EC Engines)

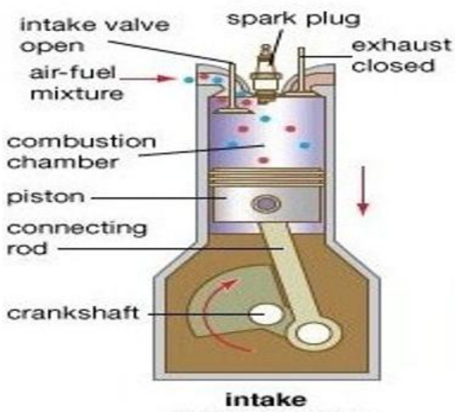
External combustion engines are those in which combustion takes place outside the engine.

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.



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

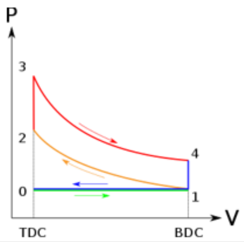
- ▶ Nature of thermodynamic cycle
- ▶ Ignition systems
- ▶ Fuel used
- ▶ Arrangement of cylinders
- ▶ Cooling systems
- ▶ Fuel supply systems

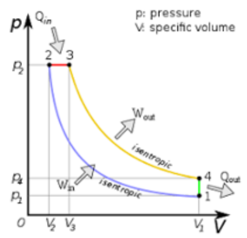
<u>Number of Strokes Per Cycle</u>:

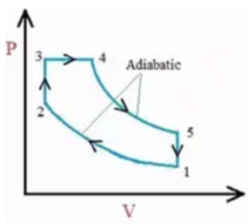
- ➢ I.C. engines can be classified as **four-stroke engines (4S)** and **two-stroke engines (2S).**
- ➢ In four-stroke engines, the thermodynamic cycle is completed in four strokes of the piston or two revolutions of the crankshaft whereas, in two-stroke engines, the thermodynamic cycle is completed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







<u>Ignition Systems:</u>

- ➢ 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.

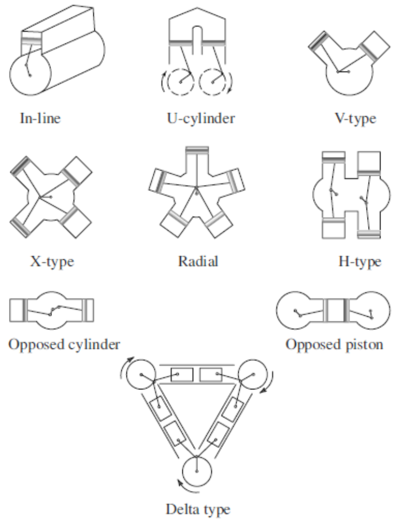
<u>Fuel Used:</u>

- ➢ 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.

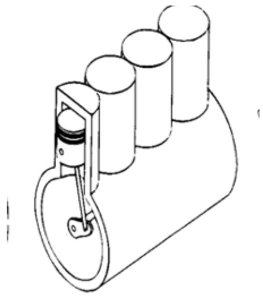
Arrangement of Cylinders:

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

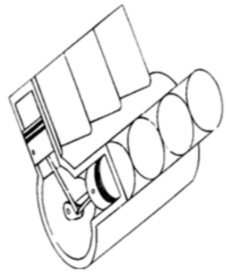
- A number of cylinder arrangements are popular with designers. The details of various cylinder arrangements are shown.



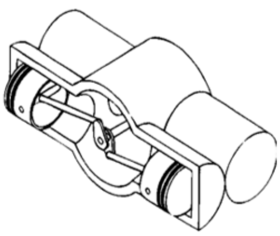
In-line Engine : The in-line engine is an engine with one cylinder bank, i.e. all cylinders are arranged linearly, and transmit power to a single crankshaft. This type is quite common with automobile engines. Four and six cylinder in-line engines are popular in automotive applications.



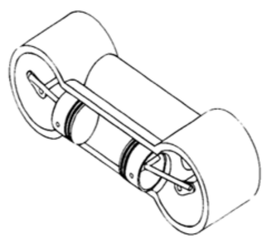
'V' Engine : In this engine there are two banks of cylinders (i.e., two in line engines) inclined at an angle to each other and with one crankshaft. Most of the high powered automobiles use the 8 cylinder 'V' engine, four in-line on each side of the 'V'. Engines with more than six cylinders generally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



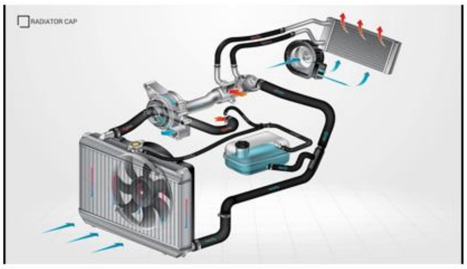
Radial Engine :

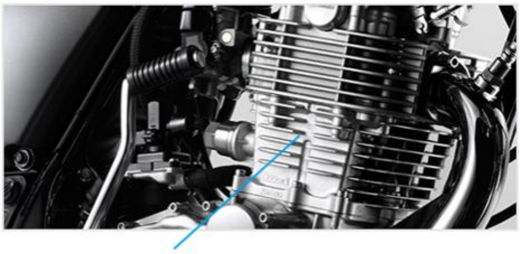
Radial engine is one where more than two cylinders in each row are equally spaced around the crankshaft. The radial arrangement of cylinders is most commonly used in conventional air-cooled aircraft engines. Pistons of all the cylinders are coupled to the same crankshaft.

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:

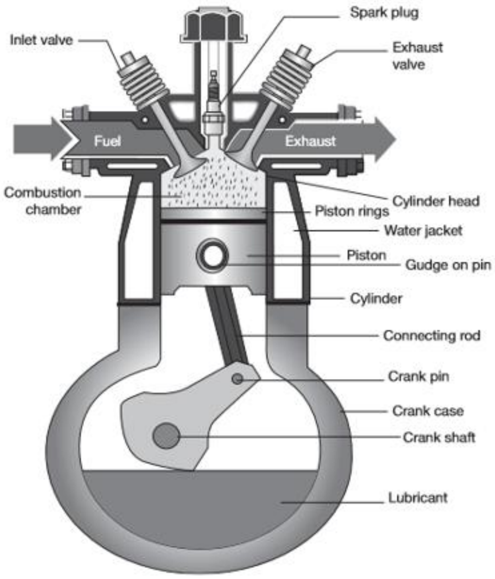
(a) Carburetor engine,

(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:

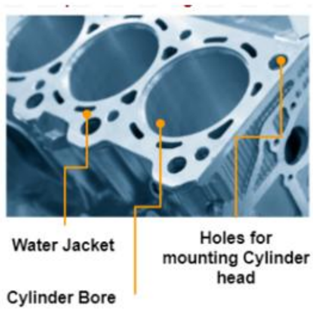


Cylinder:

- 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.

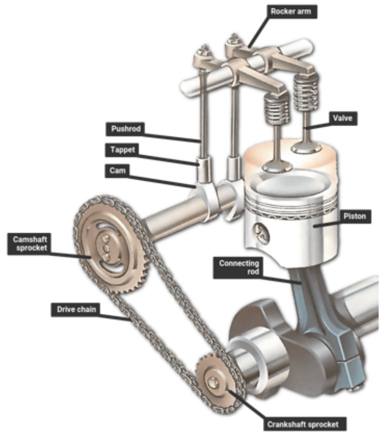
Connecting Rod:

- 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:

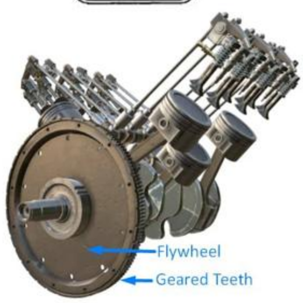
- Normally, the two valves are used for each cylinder, which may be of mushroom shaped poppet type.

- 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.

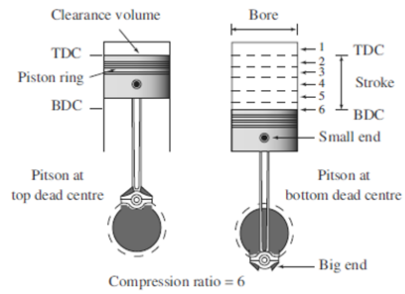
Flywheel:



- 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.

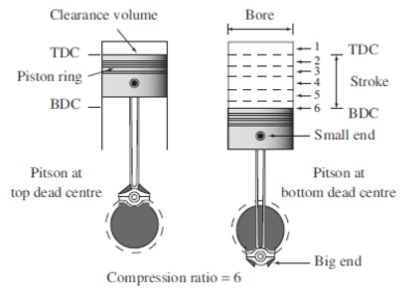
Stroke (L) : The nominal distance through which a working piston moves between two successive reversals of its direction of motion is called the stroke and is designated by the letter L.

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



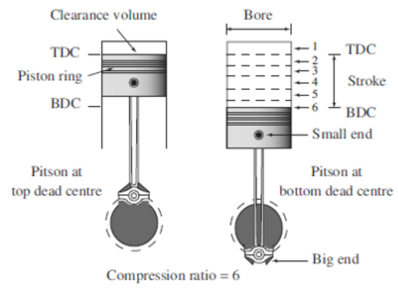
(i) Top Dead Centre (TDC) : It is the dead centre when the piston is farthest from the crankshaft.

(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).

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

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^{o} of crankshaft rotation and hence a four-stroke cycle is completed through 720^{o} 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;

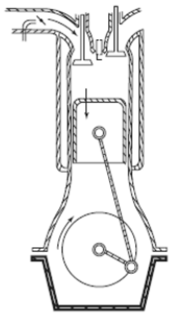
(ii) compression stroke;

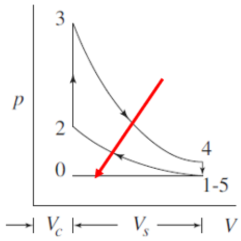
(iii) expansion or power stroke and

(iv) exhaust stroke.

Suction Stroke:

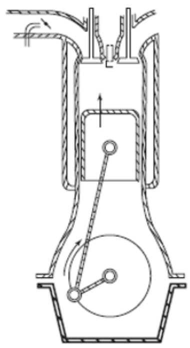
- Suction stroke 0→1 starts when the piston is at the top dead centre and about to move downwards.
- The inlet valve is assumed to open instantaneously and at this time the exhaust valve is in the closed position.
- Due to the suction created by the motion of the piston towards the bottom dead centre, 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.

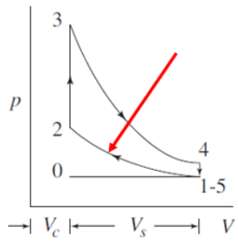




Compression Stroke:

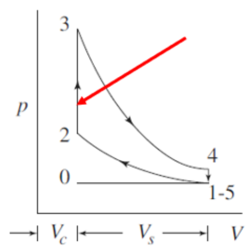
- The charge taken into the cylinder during the suction stroke is compressed by the return stroke of the piston 1→2.
- During this stroke both inlet and exhaust valves are in closed position.
- The mixture which fills the entire cylinder volume is now compressed into the clearance volume.



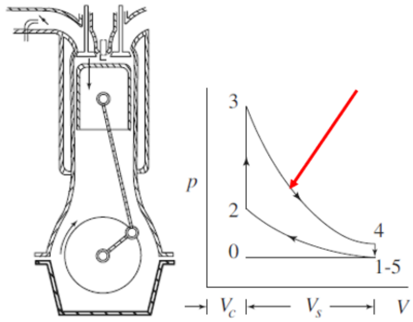


Compression Stroke:

- 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.

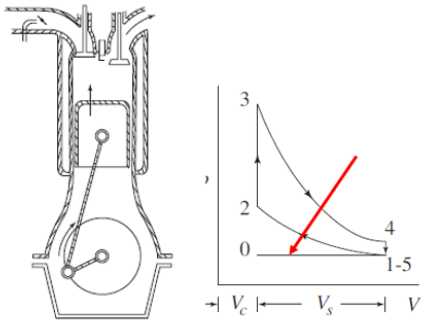


Expansion or Power Stroke :



- 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.

Exhaust Stroke:

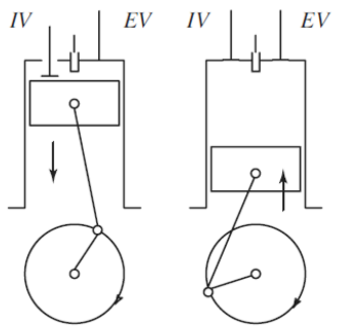


- At the end of the expansion stroke the exhaust valve opens instantaneously and the inlet valve remains closed.
- The pressure falls to atmospheric level a part of the burnt gases escape.
- The piston starts moving from the bottom dead centre to top dead centre (stroke 5→0) and sweeps the burnt gases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

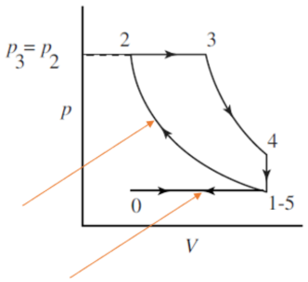
- The four-stroke CI engine is similar to the four-stroke SI engine but it operates at a much higher compression ratio. The compression ratio of an SI engine is between 6 and 10 while for a CI engine it is from 16 to 20.
- In the CI engine during suction stroke, air, instead of a fuel-air mixture, is 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 carburetor and ignition system necessary in the SI engine are not required in the CI engine.

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



(a) Suction (b) Compression

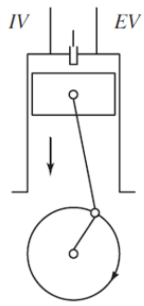
Compression Stroke: Air inducted during the suction stroke is compressed into the clearance volume. Both valves remain closed during this stroke.



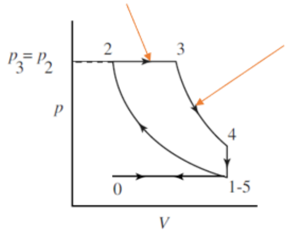
Expansion Stroke : Fuel injection starts nearly at the end of the compression stroke.

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.



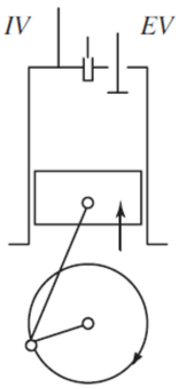
(c) Expansion



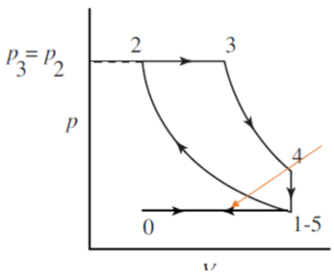
Exhaust Stroke :

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.
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.
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.

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.

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.

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

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

Were,

n= Number of cylinders

Pm = Indicated mean effective pressure in Pa or N/m²

L= Length of stroke in m

A= Area of piston m²

N= Speed of the engine on rpm

For 4-stroke engine: K= ½
For 2-stroke engine: K = 1

iii) <u>Brake Power</u> – 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,

$$BP = \frac{2\pi NT}{60 \times 1000} \qquad (expressed\ in\ kW)$$

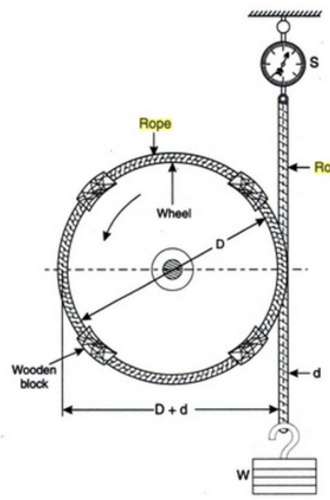
where
N = Crank speed in rpm; T = Torque in N-m

- 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.



Therefore,

$$\therefore \quad \textbf{Braking torque,}$$

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

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

iv) <u>Friction Power</u> – 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.

<u>v) Mechanical efficiency</u> - 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.

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

vi) <u>Thermal efficiency</u> – 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** = $\eta_{ith} = \frac{IP}{CV \times m_f}$

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

  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.

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** = $\frac{\textbf{Mass of fuel consumed in kg/hr}}{\textbf{Indicated Power in kW}}$

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

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

1) <u>Brake Power (BP)</u>

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

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) <u>Mechanical Efficiency</u>

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

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.

Solution:

1) <u>Brake Power</u>

We know that brake power is given by

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

2) <u>Mechanical efficiency</u>

We know that mechanical efficiency is given by,

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

3) <u>Brake Thermal Efficiency</u>

We know that brake thermal efficiency is given by,

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

4) <u>Indicated Thermal Efficiency</u>

We know that indicated thermal efficiency is given by,

$$\eta_{Ith} = \frac{IP}{m_f\times CV} = \frac{24.54}{\frac{0.1\times0.78\times1000}{1000\times60}\times43900} = 43\%$$

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.

We know that,

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

Therefore,

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

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

We have,

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

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

We know that,

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

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

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,

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

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

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

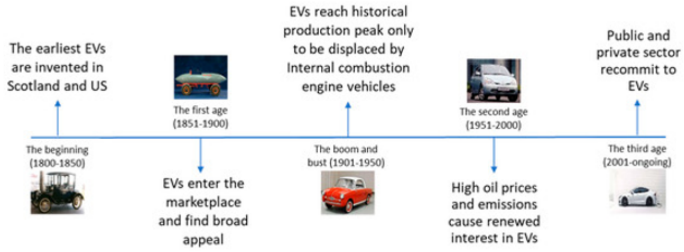
$$BSFC = \frac{m_f}{BP} = \frac{1.9057}{5} = 0.3811 kg / kWhr$$

INTRODUCTION TO ELECTRIC AND HYBRID VEHICLES

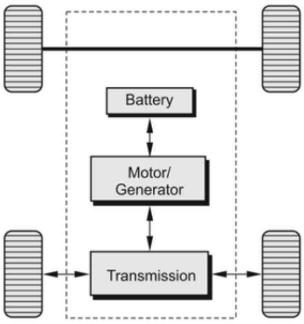
- The issues like global warming, depleting fossil fuel reserves, and greenhouse gas (GHG) emissions need dire attention for ensuring a sustainable future.

- 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

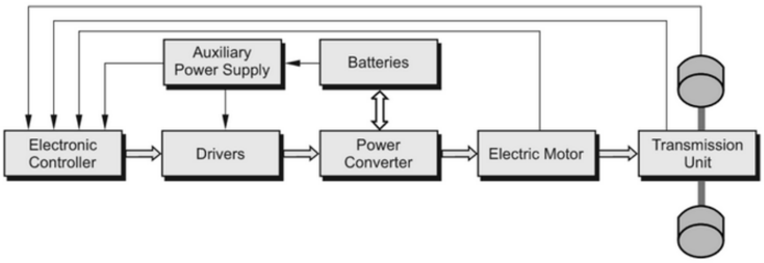


- Electric vehicles are defined as vehicles which use an electric motor for propulsion.

- 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.

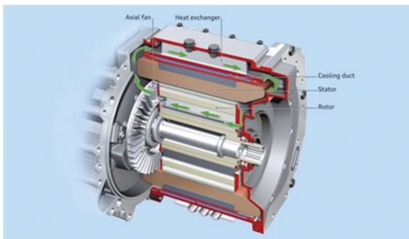
- EVs include a large range of vehicles from electric two wheelers, three wheelers (rickshaws), cars and electric buses and trucks.

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.

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.

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.

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.

Classification of EVs –

- There are 3 types of electric vehicle:

  i) Battery Electric Vehicle (BEV)

  ii) Hybrid Electric Vehicle (HEV)

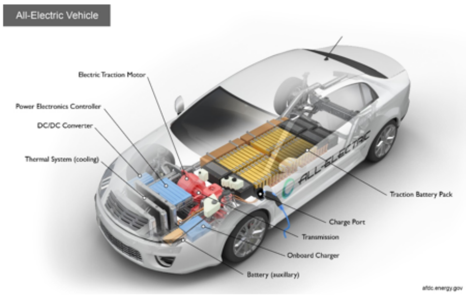
  iii) Plug in Hybrid Electric Vehicle (PHEV)

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.

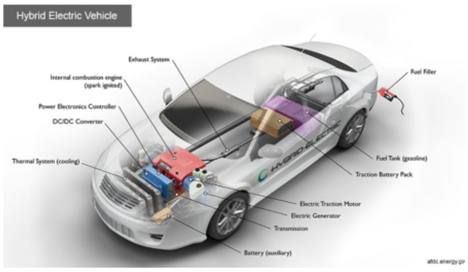


Hybrid Electric Vehicle (HEV) –

- 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.



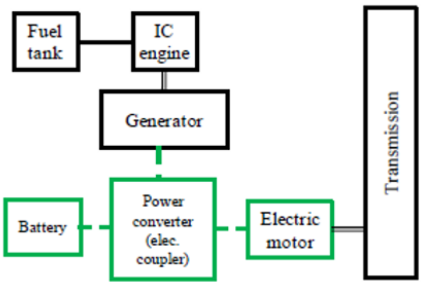
Hybrid Electric Vehicle (HEV) – Architectures

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).



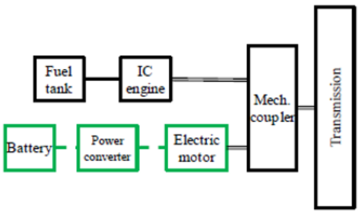
Hybrid Electric Vehicle (HEV) – Architectures

ii) Parallel Architecture

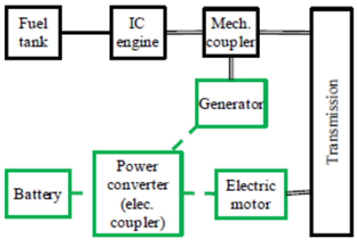
- The parallel HEV allows both ICE and electric motor (EM) to deliver power to drive the wheels.

- 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.

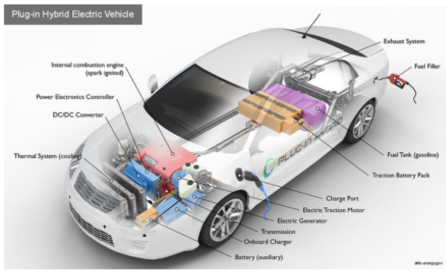


iii) Series - Parallel Architecture



- 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.

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.

Electric Vehicles (EVs)

Advantages:

1. **Zero Emissions:** No tailpipe emissions; environmentally friendly.
2. **Lower Operating Cost:** Electricity is cheaper than gasoline, and maintenance is lower (fewer moving parts).
3. **Quiet Operation:** EVs are very quiet, reducing noise pollution.
4. **High Efficiency:** Electric motors are more energy-efficient than internal combustion engines.
5. **Government Incentives:** Tax rebates, subsidies, and perks (e.g., HOV lane access).

Disadvantages:

1. **Limited Range:** Most EVs have shorter driving ranges than gasoline cars.
2. **Long Charging Time:** Charging takes longer than refueling a gas tank.
3. **Charging Infrastructure:** Still developing in some regions.
4. **High Initial Cost:** Generally more expensive upfront, although costs are dropping.
5. **Battery Degradation:** Over time, battery performance and capacity may decline.

Hybrid Vehicles (HEVs)

Advantages:

1. **Better Fuel Economy:** Combines a gasoline engine with an electric motor for improved mileage.
2. **Lower Emissions:** Produces fewer emissions than conventional vehicles.
3. **No Range Anxiety:** Uses gasoline when the battery runs low—no charging needed.
4. **Regenerative Braking:** Recovers energy during braking to recharge the battery.
5. **Widely Available:** More models and choices compared to EVs.

Disadvantages:

1. **More Complex Mechanism:** Dual power systems mean more components that can fail.
2. **Higher Maintenance Costs:** Though less than conventional cars, can be costlier than EVs.
3. **Still Uses Fossil Fuels:** Not a completely clean option.
4. **Smaller Battery:** Limited electric-only range.
5. **Initial Cost:** Higher than conventional vehicles, but often less than full EVs.