Chapter 1: FUNDAMENTAL CONCEPTS OF THERMODYNAMICS AND VARIOUS THERMODYNAMIC PROCESSES

- Thermodynamics is that branch of science which deals with energy transfer
- A system may be closed, open or isolated system
- A homogeneous system is one which consists of a single phase
- A heterogeneous system is one which consists of two or more phases.
- A property of a system is a characteristic of the system which depends upon its state, but not upon how the state is reached
- Intensive properties do not depend on the mass of the system
- Extensive properties depend on the mass of the system.
- When a path is completely specified then the change of state is called a process.
- A system is in thermodynamic equilibrium if there is no change in any thermodynamic properties of a system where it is isolated from its surroundings
- A quasi static process can be viewed as a sufficiently slow process which allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.
- The energy which crosses the system boundaries is called transient energy
- Temperature is an intensive property of a thermodynamic system.
- At absolute zero temperature the volume of a gas becomes zero
- The absolute scale related to Celsius scale is known as Kelvin -scale.

Define state, property and process. Explain the concept of cyclic process.

OR

Define thermodynamic state, path, process and cycles

Ans. State of a system indicates the specific condition of a system.

Property/Properties are those observable characteristics of system which can be used for defining it.

Process: The mode in which the change of state of a system takes place is termed as process.

Cyclic process: It refers to a typical sequence of processes in such a fashion that the initial and final states are identical.
Define heat and work.

Ans. Heat may be termed as the energy interaction across the system boundary which occurs due to temperature difference only.

Work is done when the point of application of a force moves in the direction of force.

OR

Work is defined as the energy transferred (without the transfer of mass) across the boundary of a system because of an intensive property difference other than temperature that exists between the system and surroundings.

Define the terms: system, boundary, surroundings and universe.

Ans. System: A thermodynamic system represents a specified quantity of matter under consideration to analyse a problem, so as to study the change in properties of the specified quantity of matter due to exchange of energy—in the form of heat and work.

Boundary: The thermodynamic system and surroundings are separated by an envelope is called boundary of system.

Surroundings: is defined as everything outside the system.

Universe: System and surroundings when put together result in universe. Universe = System + Surroundings.

State Zeroth law of thermodynamics.

Ans. It states if the bodies A and B are in thermal equilibrium with a third body C separately, then the two bodies A and B shall also be in thermal equilibrium with each other.

Define thermodynamic equilibrium Discuss its various aspects also

Ans. If in a system, the temperature and pressure at all parts is same, also there is no velocity gradient and chemical equilibrium is also attained then the system is in thermodynamic equilibrium. For acute of thermodynamic equilibrium system should always be in mechanical thermal and chemical equilibrium.
What is displacement work?

Ans. Work is said to be done when a force moves through a distance in a piston cylinder arrangement (Fig 1) if the part of boundary of system undergoes a displacement under the action of pressure, then work done W is force (i.e. product of pressure and area) x distance moved by the piston in the direction of force.

The piston moves outwards because of the expansion of system i.e. gas. It can be represented on p-V diagram as shown in Fig 2

\[
W.D; \quad W = \text{force} \times \text{distance moved} \\
= (p \times A) \times \text{distance moved} \\
= pA \times dx \\
= p(Adx)
\]

Define Internal energy. Is it a function of state or process?

Ans. Energy possessed by a substance because of molecular arrangement and motion molecules is known as Internal energy. It is solely dependent on the initial and final states the system that means it is a point function and hence a property.

If you compress air in a compressor, its temperature rises? Why?

Ans. If air is compressed in a compressor, the volume of air is decreased. Due to decrease in volume, the air molecules collide with each other and in the process get energised and hence, K.E. of these molecules increases and finally the temperature rises.

How is the property of system classified? Explain with examples.

Ans. Classification of property of a system is as follows:

1. **Extensive properties**: The properties which are dependent on the mass a system are known as extensive properties. Volume, mass, internal energy, enthalpy and entropy are the examples of extensive properties.

2. **Intensive properties**: The properties which are independent of the mass of system are known as intrinsic properties. Intensive properties are independent of the size of system.
Define heat. Is it the property of system?

**Ans.** Heat is a type of energy which is transferred beyond the boundary of a system because of the difference in temperature between system and surroundings. No heat is not a property of system because it is not dependent on the end states but depends upon the path followed to achieve a particular state.

Differentiate between high grade and low grade energy. Giving examples.

**Ans.** Energy which can be completely transformed in the shaft work without any loss is known as high grade energy. Mechanical and electrical energy are the examples of high grade energy.

Energy which cannot be completely converted into shaft work/mechanical work is-known as low grade energy. Heat energy and nuclear energy are the examples of low grade energy.

What are point and path functions?

**Ans.** If for a given state, there is a definite volume for each property then the property is known as a point function. The differentials of point function are exact differentials. For e.g. pressure temperature volume entropy and enthalpy etc. These type of thermodynamic properties only depend on end states. Properties which are not thermodynamic are called path functions. For e.g. work and heat. These are dependent on the path taken from one state to the other but are independent of other states. Path functions are inexact differentials.

What is an irreversible process? Give an example of irreversible process.

**Ans.** A process, which involves heat transfer due to finite difference of temperature between the system and surroundings, is known as an irreversible process Fluid friction between the molecules because of turbulence due, to high speeds is an example of an irreversible process.
Differentiate between universal gas constant and characteristic gas constant

Ans. Characteristic gas constant
From the characteristic gas equation,
\[ pV = mRT \]
\[ R = \frac{pV}{mT} \]

- \( P \): pressure
- \( V \): volume
- \( m \): mass
- \( T \): temperature

Units of \( R \) are J/kg K and \( R \) for air is 287 J/kg K
Value of gas constant \( R \) is different for different gases

**Universal gas constant**: The product of characteristic gas constant and molecular weight of an ideal gas is known as universal gas constant.

\[ R_{\text{mol}} = M \cdot R \]

Also \( R_{\text{mol}} \) (for air) = 8314 J/kg mol °K.
Where \( M \) = Molecular weight of an ideal gas
\( R \) = Characteristic gas constant.

---

**How Zeroth law of thermodynamics is applied in thermometry?**

Ans. Zeroth law states that if two systems are each in thermal equilibrium with a third system separately then two systems are also in thermal equilibrium with each other. It provides the basis for the measurement of temperature of a system.

---

**Classify the thermodynamic system and explain them with the help of the simple diagrams.**

Ans. A thermodynamic system represents a fixed quantity of matter under consideration to determine the changes in its properties because of energy transfer between system and surroundings. The thermodynamic system can be classified as

1. Open system 2. Closed system 3. Isolated system

**Open system**: When mass flow of substance takes place simultaneously with the transfer of energy, the system is known as an open system.

A steam boiler and water heater are examples of an open system.
Fig. shows an open vessel in which water is heated. The steam starts flowing upwards when water starts boiling. This shows steam along with heat flows outside the system.

**Closed system:** If in a system only heat and work energy are transferred across the boundaries of system, then it is said to be a closed system.

Fig. shows a closed vessel in which heat is given to water. Steam starts building inside the vessel, but heat flows outside the boundary of the system.

**Isolated system:** A system in which neither mass flow of substance nor transfer of energy takes place is known as an isolated system. An insulated flask containing hot water is an example of an isolated system.

---

- **Define enthalpy, why does the enthalpy of an ideal gas depend only on temperature? Discuss**

  **Ans.** Enthalpy of a substance is given by the sum of internal energy and displacement energy (product of pressure and volume).
  
  Mathematically,
  
  Enthalpy is given by,
  
  $$H = U + pV,$$
  
  where $U =$ Internal energy and $pV =$ flow work

  For a unit mass, specific enthalpy,
  
  $$h = \frac{H}{m} = \frac{U}{m} + \frac{pV}{m} = u + pv$$
because for a perfect or an ideal gas
\[ u = C_v T \text{ and } pV = RT \]
\[ h = T (C_v + R) = C_p T \]

where \( C_p \) = specific heat or constant pressure
Which is a constant quantity for an ideal gas.

Also, when a gas is heated at a constant pressure, the heat supplied to gas is utilised for following two purposes:
1. To raise the temperature of gas. This heat remains within gas and represents increase in internal energy.
2. To do some external work during expansion.

➢ Air standard Otto Cycle

Air standard Otto cycle on (a) P-v diagram (b) T-s diagram
Processes:

0-1: a fresh mixture of fuel-air is drawn into the cylinder at constant pressure

1-2: isentropic compression

2-3: energy addition at constant volume

3-4: isentropic expansion

4-1: combustion products leave the cylinder

1-0: the piston pushes out the remaining combustion products at constant pressure

Since the net work done in processes 0-1 and 1-0 is zero, for thermodynamic analysis, we consider the 1-2-3-4 only.

Otto Thermodynamic Cycle is used in all internal combustion engines.

The figure shows a p-V diagram of the Otto cycle. Using the engine stage numbering system, we begin at the lower left with Stage 1 being the beginning of the intake stroke of the engine. The pressure is near atmospheric pressure and the gas volume is at a minimum.

Between Stage 1 and Stage 2 the piston is pulled out of the cylinder with the intake valve open. The pressure remains constant, and the gas volume increases as fuel/air mixture is drawn into the cylinder through the intake valve.

Stage 2 begins the compression stroke of the engine with the closing of the intake valve.

Between Stage 2 and Stage 3, the piston moves back into the cylinder, the gas volume decreases, and the pressure increases because work is done on the gas by the piston.

Stage 3 is the beginning of the combustion of the fuel/air mixture. The combustion occurs very quickly and the volume remains constant. Heat is released during combustion which increases both the temperature and the pressure, according to the equation of state.

Stage 4 begins the power stroke of the engine.

Between Stage 4 and Stage 5, the piston is driven towards the crankshaft, the volume in increased, and the pressure falls as work is done by the gas on the piston.

At Stage 5 the exhaust valve is opened and the residual heat in the gas is exchanged with the surroundings. The volume remains constant and the pressure adjusts back to atmospheric conditions.
Stage 6 begins the exhaust stroke of the engine during which the piston moves back into the cylinder, the volume decreases and the pressure remains constant. At the end of the exhaust stroke, conditions have returned to Stage 1 and the process repeats itself.

During the cycle, work is done on the gas by the piston between stages 2 and 3. Work is done by the gas on the piston between stages 4 and 5. The difference between the work done by the gas and the work done on the gas is the area enclosed by the cycle curve and is the work produced by the cycle. The work times the rate of the cycle (cycles per second) is equal to the power produced by the engine.

The area enclosed by the cycle on a p-V diagram is proportional to the work produced by the cycle

The thermal efficiency of the cycle is given by

$$\eta = \frac{W_{net}}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

where $Q_1$ and $Q_2$ denote the energy absorbed and rejected as heat respectively.

For a constant volume process $Q=\Delta U$. If $m$ is the mass of the air which is undergoing the cyclic process,

$$\Delta U = mC_v \Delta T$$

Energy is absorbed during the process 2-3

Energy is rejected during the process 4-1

Hence,
\[ Q_1 = U_3 - U_2 = mC_v(T_3 - T_2) \]
\[ Q_2 = U_4 - U_1 = mC_v(T_4 - T_1) \]

\[ \therefore \eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} \]

For an ideal gas undergoing an isentropic process (process 1-2 and 3-4),

\[ T^\gamma v^{\gamma-1} = \text{constant} \]

Hence,

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

\[ \frac{T_4}{T_3} = \left( \frac{v_3}{v_4} \right)^{\gamma-1} \]

and

But \( v_1 = v_4 \) and \( v_2 = v_3 \). Hence we get,

\[ \frac{T_1}{T_2} = \frac{T_4}{T_3} \text{ or } \frac{T_1}{T_4} = \frac{T_2}{T_3} \]

\[ 1 - \frac{T_1}{T_4} = 1 - \frac{T_2}{T_3} \text{ or } \frac{T_4 - T_1}{T_4} = \frac{T_3 - T_2}{T_3} \]
\[
\frac{T_4 - T_1}{T_3 - T_2} = \frac{T_4}{T_3} = \frac{T_1}{T_2}
\]

\[
\eta = 1 - \frac{T_1}{T_2} = 1 - \left( \frac{v_2}{v_1} \right)^{\gamma - 1} = 1 - \left( \frac{1}{r_0} \right)^{\gamma - 1}
\]

Hence,

Where the compression ratio \( r_0 \) is defined as

\[
r_0 = \frac{v_1}{v_2}
\]

Sometimes it is convenient to express the performance of an engine in terms of Mean effective Pressure, \( P_m \), defined as the ratio of Net work done to Displacement volume

\[
P_{m2} = \frac{W}{v_1 - v_2}
\]

\[
W = P_m (v_1 - v_2)
\]

Thermal efficiency of the ideal Otto cycle as a function of compression ratio \( \gamma = 1.4 \)
Air standard Diesel cycle

Diesel cycle on (a) P-v diagram (b) T-s diagram

Processes:

0-1: fresh air is drawn into the cylinder
1-2: isentropic compression
2-3: constant pressure energy addition
3-4: isentropic expansion
4-1: combustion products leave the cylinder
1-0: remaining combustion products are exhausted at constant pressure

Defining cutoff ratio, $r_c$ as,

$$r_c = \frac{v_3}{v_2}$$

For a constant pressure process (2-3),
\[ Q = \Delta H. \]

Hence, the energy addition during process 2-3,

\[ Q_1 = H_3 - H_2 = m(h_3 - h_2) = mC_p(T_3 - T_2) \]

where \( m \) is the mass of gas undergoing the cyclic change.

The energy rejection during the process 4-1,

\[ Q_2 = U_4 - U_1 = m(u_4 - u_1) = mC_v(T_4 - T_1) \]

The thermal efficiency, \( \eta \) is given by

\[
\eta = \frac{Q_1 - Q_2}{Q_1} = \frac{mC_p(T_3 - T_2) - mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)}
\]

\[
\eta = 1 - \frac{T_4 - T_1}{\gamma(T_3 - T_2)} = 1 - \frac{T_1 \left( \frac{T_4}{T_1} - 1 \right)}{T_2 \gamma \left( \frac{T_3}{T_2} - 1 \right)}
\]

Since the process 1-2 is isentropic,

\[
\frac{T_1}{T_2} = \left( \frac{v_2}{v_1} \right)^{\gamma - 1} = \left( \frac{1}{r_0} \right)^{\gamma - 1}
\]

Since the process 4-1 is a constant volume process,

\[
\frac{T_4}{T_1} = \frac{P_4}{P_1} = \frac{P_4}{P_3} \left( \frac{P_3}{P_1} \right) = \frac{P_4}{P_3} \left( \frac{P_2}{P_1} \right)
\]

since \( P_2 = P_3 \)
The processes 1-2 and 3-4 are isentropic. Hence,

\[
\frac{P_4}{P_3} = \left(\frac{v_3}{v_4}\right)\gamma \quad \text{and} \quad \frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)\gamma
\]

Hence we get,

\[
\frac{T_4}{T_1} = \left(\frac{v_3}{v_4}\right)^\gamma \left(\frac{v_1}{v_2}\right)^\gamma = \left(\frac{v_3}{v_2}\right)^\gamma = r_c^\gamma
\]

For the constant pressure process,

\[
\frac{T_3}{T_2} = \frac{v_3}{v_2} = r_c
\]

Hence the efficiency becomes,

\[
\eta = 1 - \frac{1}{\gamma r_c^{\gamma-1}} \left[ \frac{r_c^{\gamma} - 1}{r_c^{\gamma} - 1} \right]
\]

The mean effective pressure of an air standard diesel cycle is given by,

\[
P_m = P_i \frac{\gamma r_c^{\gamma} (r_c^{\gamma} - 1) - r_c^{\gamma} (r_c^{\gamma} - 1)}{(\gamma - 1)(r_c^{\gamma} - 1)}
\]
Air standard Dual cycle

Energy addition is in two stages: Part of energy is added at constant volume and part of the energy is added at constant pressure.

Energy added, $q_1$

$$q_1 = C_v (T_3 - T_2) + C_p (T_4 - T_3)$$

Energy rejected, $q_2$

$$q_2 = C_v (T_5 - T_1)$$
Thermal efficiency, $\eta$

$$\eta = 1 - \frac{q_2}{q_1}$$

$$\eta = 1 - \frac{C_v(T_5 - T_1)}{C_v(T_3 - T_2) + C_p(T_4 - T_3)}$$

$$\eta = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)}$$

The efficiency can be expressed also in terms of,

Compression ratio, $r_0 = \frac{V_1}{V_2}$

Cut-off ratio, $r_c = \frac{V_4}{V_3}$

Constant volume pressure ratio, $r_{vp} = \frac{P_3}{P_2}$

➤ **Explain ISOBARIC and ISOCHRONIC processes**

Thermodynamic process may be defined as the energetic evolution of a thermodynamic system proceeding from an initial state to a final state. Paths through the space of thermodynamic variables are often specified by holding certain thermodynamic variables constant.
The pressure-volume conjugate pair is concerned with the transfer of mechanical or dynamic energy as the result of work.

* An isobaric process occurs at constant pressure (P=constant). An example would be to have a movable piston in a cylinder, so that the pressure inside the cylinder is always at atmospheric pressure, although it is isolated from the atmosphere. In other words, the system is dynamically connected, by a movable boundary, to a constant-pressure reservoir.

The work done by the isobaric process is
\[ \Delta W = \int P \, dV = P \int dV = P(V_f - V_i) = P \Delta V \]

* An isochoric process is one in which the volume is held constant (V=constant), meaning that the work done by the system will be zero. It follows that, for the simple system of two dimensions, any heat energy transferred to the system externally will be absorbed as internal energy. An isochoric process is also known as an isometric process or an isovolumetric process. An example would be to place a closed tin can containing only air into a fire. To a first approximation, the can will not expand, and the only change will be that the gas gains internal energy, as evidenced by its increase in temperature and pressure. Mathematically, \( \delta Q = dU \). We may say that the system is dynamically insulated, by a rigid boundary, from the environment.

The temperature-entropy conjugate pair is concerned with the transfer of thermal energy as the result of heating.
> Explain ISOTHERMAL and ADIABATIC processes

* An isothermal process occurs at a constant temperature \((T=\text{constant})\). An example would be to have a system immersed in a large constant-temperature bath. Any work energy performed by the system will be lost to the bath, but its temperature will remain constant. In other words, the system is thermally connected, by a thermally conductive boundary to a constant-temperature reservoir.

For ideal gas:

\[
\Delta W = \int P \, dV = \int \frac{nRT}{V} \, dV = nRT \int \frac{dV}{V} = nRT \ln \frac{V_f}{V_i}
\]

\[
\Delta U = \int nC_v \, dT = nC_v \Delta T.
\]

\[
\Delta Q = \Delta U - \Delta W = nC_v \Delta T - nRT \ln \frac{V_f}{V_i}
\]

* An adiabatic process is a process in which there is no energy added or subtracted from the system by heating or cooling \((\delta Q=0)\). For a reversible process, this is identical to an isentropic process. We may say that the system is thermally insulated from its environment and that its boundary is a thermal insulator. If a system has an entropy which has not yet reached its maximum equilibrium value, the entropy will increase even though the system is thermally insulated.

\[
\delta Q = dU - \delta W = 0 \quad \text{so} \quad dU = \delta W.
\]

The first law of thermodynamically state:

**The internal energy** change is equal to the **heat absorbed** minus the **work done**.

\[
\Delta U = \Delta Q - \Delta W
\]

- isothermal process: \(\Delta U = 0\), so \(\Delta Q = \Delta W\)
- adiabatic process: \(\Delta Q = 0\), so \(\Delta U = \Delta W\)
- isochoric process: \(\Delta W = 0\), so \(\Delta U = \Delta Q\)
LAWS OF THERMODYNAMICS

The four laws of thermodynamics define fundamental physical quantities (temperature, energy, and entropy) that characterize thermodynamic systems. Energy exists in many forms, such as heat, light, chemical energy, and electrical energy. Energy is the ability to bring about change or to do work. Thermodynamics is the study of energy.

The four laws of thermodynamics are:

**Zeroth law of thermodynamics:** If two systems are both in thermal equilibrium with a third systems then they are in thermal equilibrium with each other. This law helps define the notion of temperature.

**First law of thermodynamics:**
Energy can be changed from one form to another, but it cannot be created or destroyed. The total amount of energy and matter in the Universe remains constant, merely changing from one form to another.

The First Law of Thermodynamics (Conservation) states that energy is always conserved; it cannot be created or destroyed. In essence, energy can be converted from one form into another.

Heat and work are forms of energy transfer. Energy is invariably conserved but the internal energy of a closed system changes as heat and work are transferred in or out of it. Equivalently, perpetual motion machines of the first kind are impossible.

**Second law of thermodynamics:**
The Second Law of Thermodynamics states that "in all energy exchanges, if no energy enters or leaves the system, the potential energy of the state will always be less than that of the initial state." This is also commonly referred to as entropy. A watchspring-driven watch will run until the potential energy in the spring is converted, and not again until energy is reapplied to the spring to rewind it. A car that has run out of gas will not run again until you walk 10 miles to a gas station and refuel the car. Once the potential
energy locked in carbohydrates is converted into kinetic energy (energy in use or motion), the organism will get no more until energy is input again. In the process of energy transfer, some energy will dissipate as heat. Entropy is a measure of disorder: cells are NOT disordered and so have low entropy. The flow of energy maintains order and life. Entropy wins when organisms cease to take in energy and die.

OR

An isolated system, if not already in its state of thermodynamic equilibrium, spontaneously evolves towards it. Thermodynamic equilibrium has the greatest entropy amongst the states accessible to the system. Equivalently, perpetual motion machines of the second kind are impossible.

Discuss the limitations of the first law of Thermodynamics.

Limitations of the first law of thermodynamics are:

1. No restriction on the direction of the flow of heat: the first law establishes definite relationship between the heat absorbed and the work performed by a system. The first law does not indicate whether heat can flow from a cold end to a hot end or not. For example: we cannot extract heat from the ice by cooling it to a low temperature. Some external work has to be done.

2. Does not specify the feasibility of the reaction: first law does not specify that process is feasible or not for example: when a rod is heated at one end then equilibrium has to be obtained which is possible only by some expenditure of energy.

3. Practically it is not possible to convert the heat energy into an equivalent amount of work.

To overcome this limitations, another law is needed which is known as second law of thermodynamics.

The second law of thermodynamics helps us to predict whether the reaction is feasible or not and also tell the direction of the flow of heat.

It also tells that energy cannot be completely converted into equivalent work.
The Kelvin-Planck Statement:

It is impossible to construct a device which operates on a cycle and produces no other effect than the transfer of heat from a single body in order to produce work.

We prefer a less formal description of this statement in terms of a boat extracting heat from the ocean in order to produce its required propulsion work:

Kelvin-Planck Statement of the Second Law:

The Clausius Statement: It is impossible to construct a device which operates on a cycle and produces no other effect than the transfer of heat from a cooler body to a hotter body.

Clausius Statement of the Second Law:

Equivalence of the Clausius and Kelvin-Planck Statements

It is remarkable that the two above statements of the Second Law are in fact equivalent. In order to demonstrate their equivalence consider the following diagram. On the left we see a heat pump which violates the Clausius statement by pumping heat $Q_L$ from the low temperature reservoir to the high temperature reservoir without any work input. On the right we see a heat engine rejecting heat $Q_L$ to the low temperature reservoir.
If we now connect the two devices as shown below such that the heat rejected by the heat engine $Q_L$ is simply pumped back to the high temperature reservoir then there will be no need for a low temperature reservoir, resulting in a heat engine which violates the Kelvin-Planck statement by extracting heat from a single heat source and converting it directly into work.

**Mechanical and Thermal Reversibility**

Notice that the statements on the Second Law are negative statements in that they only describe what is impossible to achieve. In order to determine the maximum performance available from a heat engine or a heat pump we need to introduce the concept of Reversibility, including both mechanical and thermal reversibility. We will attempt to clarify these concepts in terms of the following example of a reversible piston cylinder device in thermal equilibrium with the surroundings at temperature $T_0$, and undergoing a cyclic compression/expansion process.
For mechanical reversibility we assume that the process is frictionless, however we also require that the process is a quasi-equilibrium one. In the diagram we notice that during compression the gas particles closest to the piston will be at a higher pressure than those farther away, thus the piston will be doing more compression work than it would do if we had waited for equilibrium conditions to occur after each incremental step. Similarly, thermal reversibility requires that all heat transfer is isothermal. Thus if there is an incremental rise in temperature due to compression then we need to wait until thermal equilibrium is established. During expansion the incremental fall in temperature will result in heat being transferred from the surroundings to the system until equilibrium is established.

In summary, there are three conditions required for reversible operation:

- All mechanical processes are frictionless.
- At each incremental step in the process thermal and pressure equilibrium conditions are established.
- All heat transfer processes are isothermal.