GOVERNMENT POLYTECHNIC, SIRSA

BRANCH : MECHANICAL ENGINEERING
SUBJECT : THERMODYNAMICS
SEMESTER : 3rd

CONTENTS

CHAPTER 1
FUNDAMENTAL CONCEPTS

1.1 INTRODUCTION TO THERMODYNAMICS

Thermodynamics is branch of physics which deals with temperature, heat and their relation to energy, radiation, work, and properties of matter. The thermodynamic term is derived from two Greek words ‘thermes’ meaning heat, and ‘dynamis’ meaning motion. Thermodynamics means heat in motion. The key concept is that heat is a form of energy corresponding to a definite amount of mechanical work. The study of thermodynamics is comprised of important laws of thermodynamics namely first law of thermodynamics, second law of thermodynamics, third law of thermodynamics and Zeroth law of thermodynamics.

The application of thermodynamic laws are found in all field of energy transfer, mainly in steam and nuclear power plants, internal combustion engine, gas turbine, air conditioning and refrigeration, air compressor and chemical process plants etc.

1.2 THERMODYNAMIC STATE

The condition of a system at any instant of time described by its physical properties is known as state of system. An operation in which properties of system change is called a change of state.

1.3 THERMODYNAMIC SYSTEM

A quantity of the matter or part of the space which is under thermodynamic study is called as system. It is shows in fig.1.1

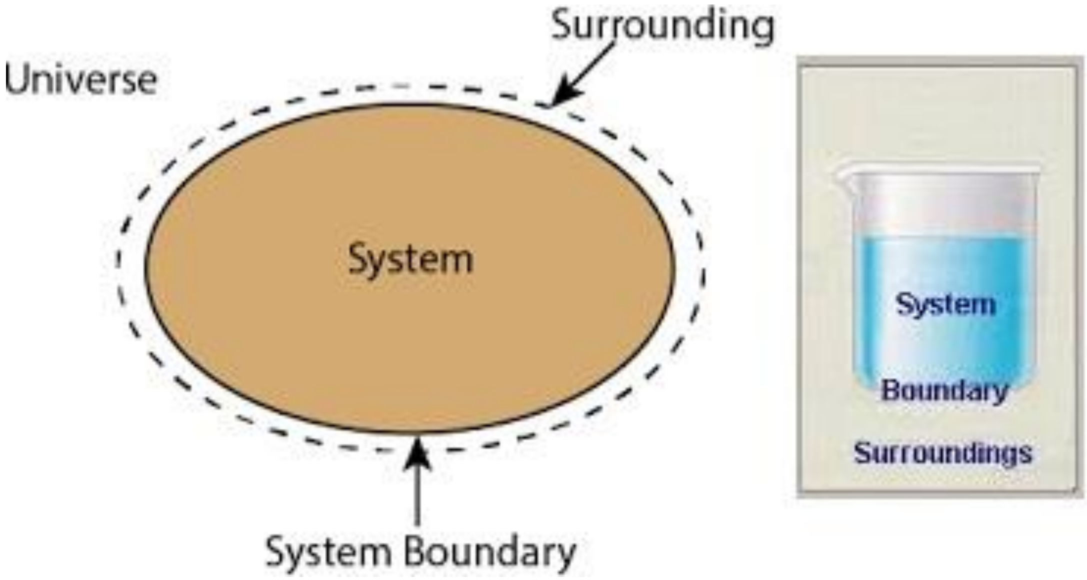


Fig. 1.1: Thermodynamic system

1.4 BOUNDARY

System and surroundings are separated by a definite border called boundary. It can be fixed or movable. System, surroundings and boundary constitute the universe.

1.5 SURROUNDING

Everything external to a thermodynamic system is called surroundings.

1.6 UNIVERSE

The system and the surroundings together make up the universe.

1.7 TYPES OF THERMODYNAMIC SYSTEMS

Thermodynamic systems can be broadly classified into three types. They are:

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

In fig. 1.2 shows the types of thermodynamic system.

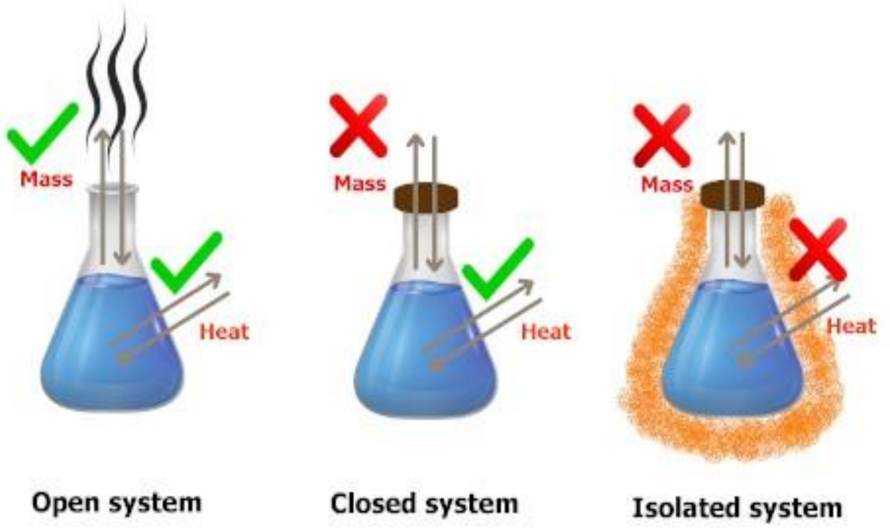


Fig. 1.2: Types of thermodynamic system

1. **Open system**

An open system is a thermodynamic system which allows both mass and energy to flow in and out of it, across its boundary.

2. **Closed system**

A closed system allows only energy (heat and work) to pass in and out of it. It does not allow mass transfer across its boundary.

3. **Isolated system**

It does not allow both mass and energy transfer across its boundary. It is more restrictive. In reality, complete isolated systems do not exist. However, some systems behave like an isolated system for a finite period of time.

However, there are some other terms by which the system or characteristics of a sytem are described. Thear are as below:

4. **Adiabatic**

The process during which work is done and no heat is transferred across the system boundary is known as adiabatic process.

5. **Homogeneous**

The system that has single or uniform phase such as like solid or liquid or gaseous is called as homogeneous system.

6. **Heterogeneous**

The system that has more than one phase i.e. the combination of solid, liquid and gaseous state is called as heterogeneous system.

7. **Macroscopic**

In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level. In other words this approach to thermodynamics is concerned with gross or all behavior. This is known as classical thermodynamics.

The values of the properties of system are their average values. For example consider a sample of a gas in a closed container. The pressure of the gas is the average value of the pressure exerted by millions of individual molecules.

8. **Microscopic**

In microscopic study, the behavior of individual atoms and molecules of a substance considered. This approach considers that the systems are made up of a very large numbers of discrete particles known as molecules. These molecules have different velocities and energies. The values of these energies are constantly changing with time.

1.8 PROPERTIES OF THE SYSTEM

The characteristics by which the physical condition of the system is described are called as properties of system. Some examples of these characteristics are: temperature, pressure, volume etc. are called as properties of system.

The system properties are of two types: extensive and intensive properties.

1. **Extensive properties of system**

   The properties of the system that depend on the mass or quantity of the system are called extensive properties. Some examples of extensive properties are: mass, volume, enthalpy, internal energy, entropy etc.

2. **Intensive properties of the system**

   These properties do not depend on the quantity of matter of the system. Some of the examples of intensive properties are: freezing point temperature, boiling point, temperature of the system, density, specific volume etc.

1.9 THERMODYNAMIC EQUILIBRIUM

A state of thermodynamic equilibrium is said to be exist in a system if no change in any macroscopic properties is registered and the system is assumed to be isolated from its surroundings. A system will be in state of thermodynamic equilibrium, if following three equilibrium conditions are satisfied:

1. Mechanical equilibrium
2. Chemical equilibrium
3. Thermal equilibrium

1. Mechanical equilibrium

A state of mechanical equilibrium is that state in which it experiences no pressure or elastic stress within it and there is no unbalanced force between the system and surrounding.

2. Thermal equilibrium

In the state of thermal equilibrium of the system, there is no exchange of heat energy between the system and surrounding. Such a state is characterized by same value of the temperature of the system and surrounding.

3. Chemical equilibrium

In the state of chemical equilibrium system does not undergo a spontaneous change in its internal composition i.e. no chemical reaction takes place in it and no transfer of matter takes place from one part of it to another part.

1.10 QUASI-STATIC PROCESS

The state of a system can change as a result of its interaction with the environment. The change in a system can be fast or slow and large or small. The manner in which a state of a system can change from an initial state to a final state is called a thermodynamic process. For analytical purposes in thermodynamics, it is helpful to divide up processes as either quasi-static or non-quasi-static. A quasi-static process refers to an idealized or imagined process where the change in state is made infinitesimally slowly so that at each instant, the system can be assumed to be at a thermodynamic equilibrium with itself and with the environment. For instance, imagine heating 1 kg of water from a temperature 20ºC to 21ºC at a constant pressure of 1 atmosphere. To heat the water very slowly, we may imagine placing the container with water in a large bath that can be slowly heated such that the temperature of the bath can rise infinitesimally slowly from 20ºC to 21ºC. If we put 1 kg of water at 20ºC directly into a bath at 21ºC the temperature of the water will rise rapidly to 21ºC in a non-quasi-static way.

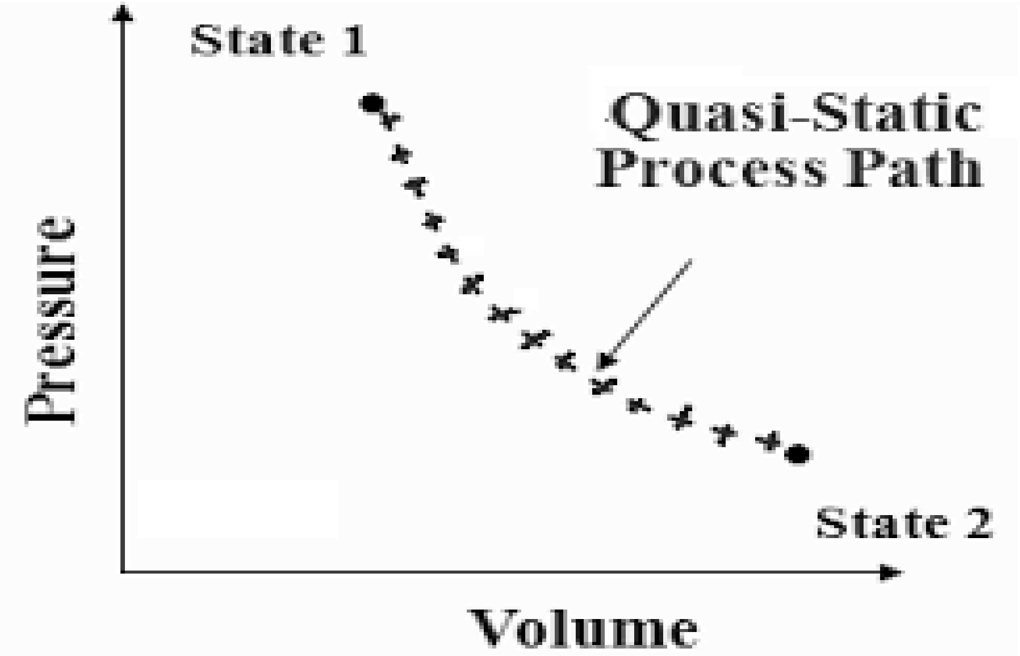


Fig. 1.3: Quasi-static process

Quasi-static processes are done slowly enough that the system remains at thermodynamic equilibrium at each instant, despite the fact that the system changes over time. The thermodynamic equilibrium of the system is necessary for the system to have well-defined values of macroscopic properties such as the temperature and the pressure of the system at each instant of the process. Therefore, quasi-static processes can be shown as well-defined paths in state space of the system. Since quasi-static processes cannot be completely realized for any finite change of the system, all processes in nature are non-quasi-static.

1.11 REVERSIBLE AND IRREVERSIBLE PROCESSES

A process which can be reversed in direction and the system retraces the same path and the same equilibrium state is known as reversible process. Fig. 1.4 shows a reversible process.

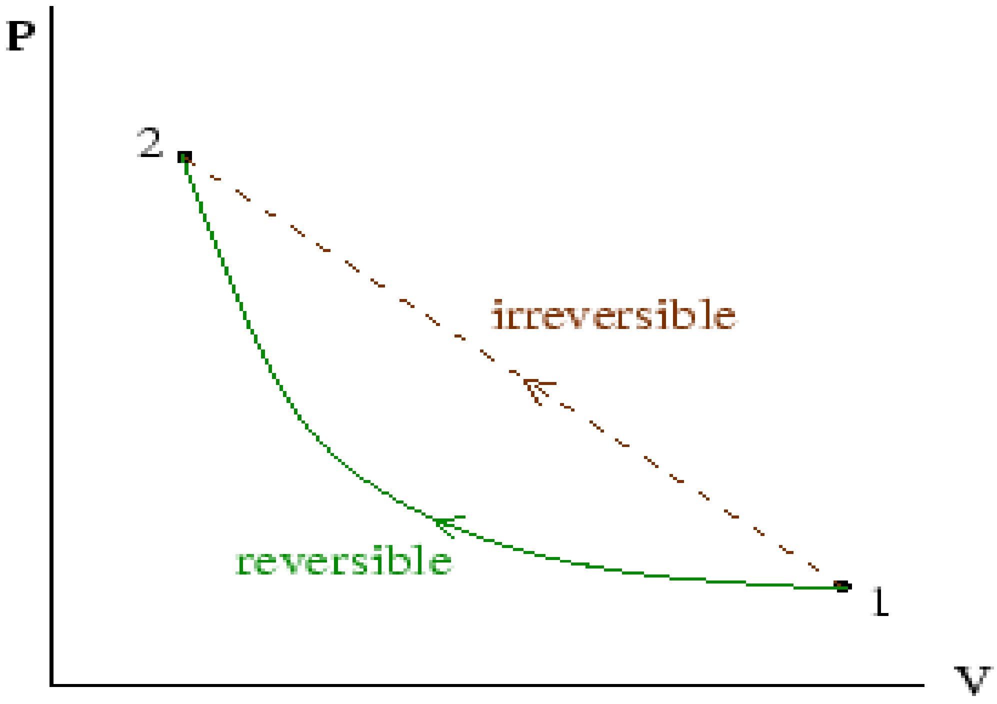


Fig. 1.4: Reversible and irreversible processes

A process said to be irreversible if a system passes through a sequence of non-equilibrium states. An irreversible process cannot come back to the original state, if made to proceed in reverse direction. Fig. 4 shows an irreversible process with dotted lines.

1.12 ZEROTH LAW OF THERMODYNAMICS

The Zeroth law of thermodynamics states that if two bodies are each in thermal equilibrium with some third body, then they are also in equilibrium with each other. Thermal equilibrium means that when two bodies are brought into contact with each other and separated by a barrier that is permeable to heat, there will be no transfer of heat from one to the other.

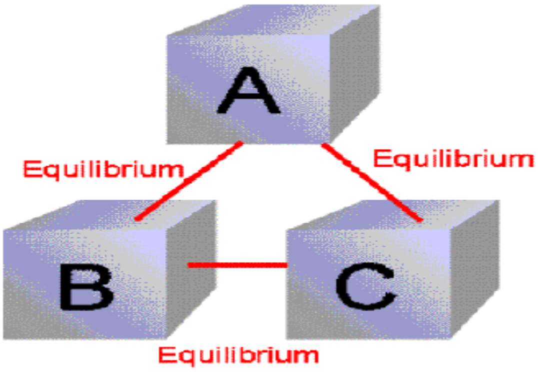


Fig. 1.5: Zeroth law of thermodynamics

1.13 PRESSURE

Pressure is a measure of the force exerted per unit area on the boundaries of a substance. The standard unit for pressure in the SI system is the Newton per square meter or pascal (Pa). Mathematically:

$$P = F/A$$

Where F is the normal force and A is the area on which force is exerted.

Atmospheric Pressure

The pressure exerted by atmospheric air on the earth surface is called atmospheric pressure. The atmospheric pressure varies with temperature and altitude above sea level.

Absolute pressure

When pressure is measured with reference to absolute vacuum pressure then it is called absolute pressure. At this pressure, the molecular momentum is zero.

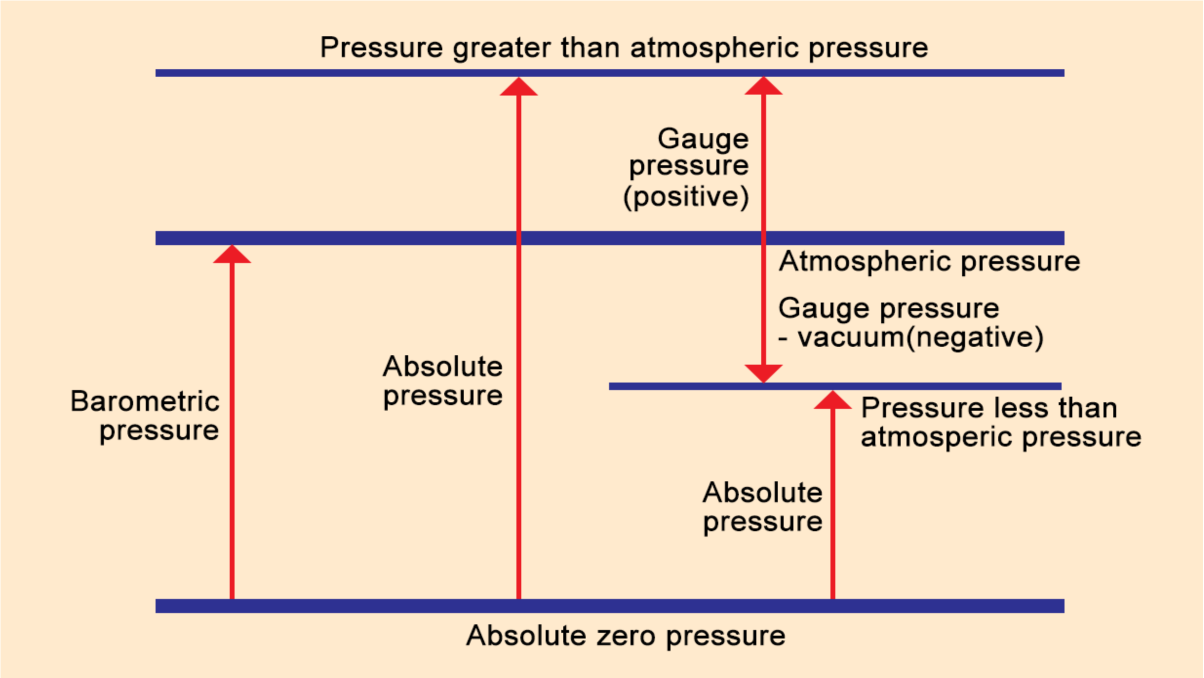


Fig. 1.6: Absolute pressure, gauge and vacuum pressure

Gauge pressure

This is the pressure measured by of pressure measuring instruments, in which atmospheric pressure is taken as datum. The atmospheric pressure is taken as zero this system. The instrument used to measure this pressure is known as pressure gauge. The pressure always used to indicate the pressure above atmospheric pressure.

Vacuum pressure

Measurement of pressure below the atmospheric pressure, in which atmospheric pressure taken as reference. This is also known as negative pressure or suction pressure. The instrument used to measure vacuum pressure is known as vacuum gauge.

1.14 VOLUME

The amount of space occupied by any substance is called volume. Its unit is m^3.

1.15 TEMPERATURE

It is an intensive property which determines the degree of hotness or the level of heat intensity of a body. The temperature of a body is measured with the help of an instrument known as thermometer.

For the measurement of temperature of body, following types of scales are used:

1. Centigrade temperature scale (°C)

Centigrade temperature scale also called Celsius temperature scale, is the scale based on 0 for the freezing point of water and 100 for the boiling point of water. Invented in 1742 by the Swedish astronomer Anders Celsius, it is sometimes called the centigrade scale because of the 100-degree interval between the defined points. The Celsius scale is in general use wherever metric units have become accepted, and it is used in scientific work everywhere.

2. Fahrenheit scale (°F)

Fahrenheit temperature scale is a scale based on 32 for the freezing point of water and 212 for the boiling point of water, the interval between the two being divided into 180 parts. The relationship between centigrade and fahrenheit scale is given by

3. Absolute temperature

It is temperature below which the temperature of any substance cannot fall. For calculations, the absolute zero temperature is taken as -273°C in case of Celsius scale and -460°F in case of fahrenheit scale. The absolute temperature in Celsius scale is called degree Kelvin (K) and in fahrenheit scale is called degree of Rankine (°R).

$$\mathbf{T\ (K) = T\ (^{\circ}K) + 273}$$

$$\mathbf{T\ (^{\circ}R) = T\ (^{\circ}F) + 460}$$

1.16 ENTHALPY

It is the sum of the internal energy added to the product of the pressure and volume of the system. It reflects the capacity to do non-mechanical work and the capacity to release heat. Enthalpy is denoted as H; specific enthalpy denoted as h.

$$\mathbf{H = U + PV}$$

1.17 INTERNAL ENERGY

It is the energy stored in a body or a system due to its molecular arrangement and motion of molecules. It is generally denoted by U. it is function of temperature. Internal energy is given by

$$\mathbf{\Delta U = mC_v (T_2 - T_1)}$$

CHAPTER 2
LAWS OF PERFECT GASES

2.1 DEFINITION OF GASES

A gas may be defined as a state of a substance, whose evaporation from its liquid state is complete. A perfect gas or an ideal gas may be defined as a gas which obeys all the gas laws under all conditions of temperature and pressure. In actual practice, no gas is perfect gas, but some real gases like oxygen, nitrogen and air etc. may be regarded as perfect gases within certain temperature and pressure limits.

2.2 EXPLANATION OF PERFECT GAS LAWS

There are mainly three variables which control the physical properties of gas: (i)Temperature of the gas (T), (ii) Pressure exerted by gas (P), (iii) Volume occupied by gas (V).

Any change in above mentioned variables is given by various laws which are based upon the experimental results.

(i) Boyle's law, (ii) Charle's law, (iii) Gay-Lussac law

I. Boyle's law

This law states, at constant temperature, the volume of an ideal gas is inversely proportional to its absolute pressure. Mathematically,

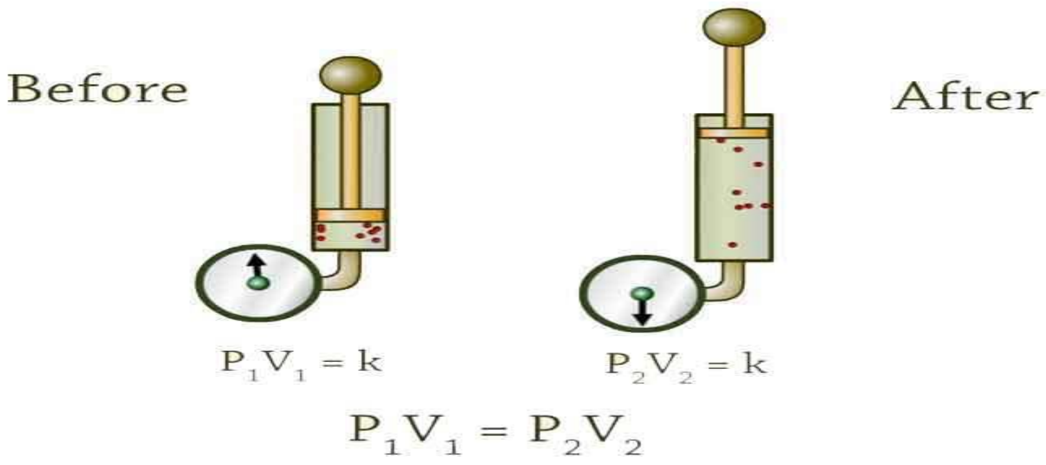
$$P \, \alpha \, \frac{1}{V}$$

Or $$PV = \text{Constant}$$

The more useful form of the above equation is

$P_1V_1 = P_2V_2 = P_3V_3 = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots = \text{constant.}$

The product of pressure and volume is constant for a fixed mass of ideal gas at fixed temperature.



II. Charle's law

At constant pressure, the volume of an ideal gas is directly proportional to its absolute temperature. The simplest statement of the law is:

$$V \propto T$$

V = volume
T = absolute temperature
(assumes pressure constant and closed system)

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

T = Temperature of the gas
V = Volume of the gas

Pressure must be constant

All perfect gases change in volume by 1/273th of its original volume at 0 ºC for every 1 ºC change in temperature, when the pressure remains constant.

Let V_o = Volume of a given mass of gas at 0 ºC
V_t = Volume of a given mass of gas at t ºC

Then according to above statement,

$$V_t = V_o + \frac{1}{273} V_o \times t$$

$$= V_o \times \left(\frac{273+t}{273}\right) = V_o \times \frac{T}{T_o}$$

$$\frac{Vt}{T} = \frac{V_o}{T_o}$$

The above statement shows that the volume of a gas goes on decreasing by 1/273th of its original volume for every 1 °C decrease in temperature. Now at a temperature of -273°C, the volume of the gas would become zero and this temperature is called absolute zero temperature.

III. Gay-Lussac law

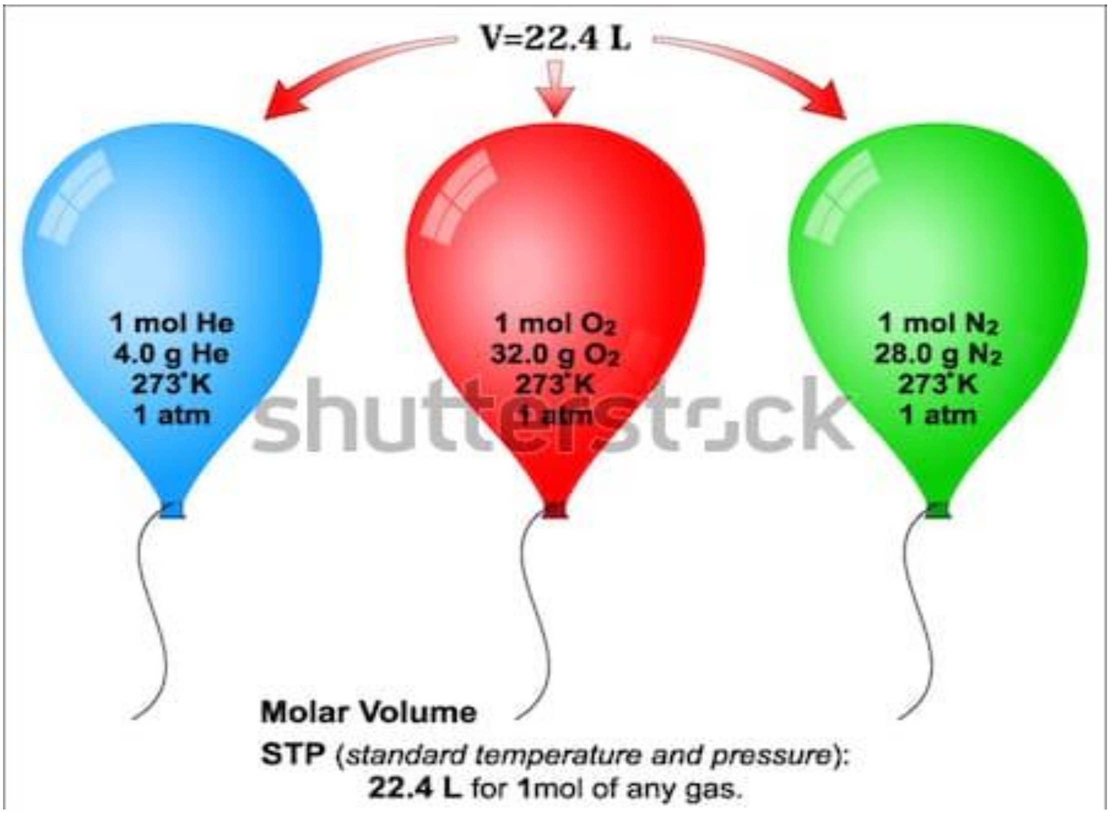
At constant volume, the pressure of an ideal gas is directly proportional to its absolute temperature. Mathematically,

$$P \propto T \quad \text{or} \quad \frac{P}{T} = Constant$$

$$\text{Or} \qquad \frac{P1}{T1} = \frac{P2}{T2} = \frac{P3}{T3} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots = \text{Constant.}$$

2.3 AVOGADRO’S LAW

It implies that under similar conditions of pressure, volume and temperatures all gases will have an equal number of molecules, independent of the weight and density of the gas.



Equal volumes of all gases at conditions of same temperature and pressure have the same number of molecules', written as:

$$V \propto n \text{ or } V/n = K$$

Where V=volume of gas;

n= Number of moles

2.4 REGNAULT'S LAW

It is states that the specific heat capacity of a gas at constant pressure (C_p) and the specific heat capacity of a gas at constant volume (C_v) do not change with change in pressure and temperature. According to this law, C_p and C_v values of a gas remain constant.

2.5 UNIVERSAL GAS CONSTANT (R)

When the molecular mass of any gas is multiplied by its specific gas constant/ characteristic gas constant (R). R is explained in the next topic. It is observed that the product R is always the same for all gases. This product is called universal gas constant and it is denoted as R. In SI system the value of the universal gas constant is 8.314 kJ/mole.K.

$$R_u = MR$$

Where M = molecular mass of gas in kg mole,

R = Gas constant.

R_u = 8314.3J/kg mole/K

2.6 GENERAL GAS EQUATION & CHARACTERISTIC GAS CONSTANT

The Combined gas law or General Gas Equation is obtained by combining Boyle's law, Charles's law, and Gay-Lussac's law. If temperature and pressure are kept constant, then the volume of the gas is directly proportional to the number of molecules of gas.

Let us consider the pressure exerted by the gas to be ‘P’

The volume of the gas be – V

Temperature be – T

Universal gas constant – R

According to Boyle’s Law,

$P \propto \frac{1}{V}$ or $V \propto \frac{1}{P}$

According to Charles’ Law,

$V \propto T$

From above two laws, we have

$V \propto \frac{1}{P}$ and T both

$V \propto \frac{T}{P}$

$PV \propto T$

PV = CT

Where C is a constant and value of C depends upon the mass and other properties of the gas. The general gas equation may be written as:

$Pv = RT$

If m is the mass of gas in kg, then the equation can be written as:

PV = mRT

Where,

R is the gas constant, called characteristic gas constant which has a value of 287 J/kgK.

2.7 SPECIFIC HEATS

The amount of heat required to raise the temperature of its unit mass through one degree. Solid and liquid have only one specific heat. Gas has mainly two types of specific heat:

a) Specific heat at constant pressure (C_p)

The amount of heat required to raise the temperature of its unit mass through one degree, when its pressure is kept constant.

$Q = mC_p dT$

b) Specific heat at constant volume (C_v)

The amount of heat required to raise the temperature of its unit mass through one degree, when its volume is kept constant.

$Q = mC_v dT$

c) Specific Index

It is the ratio of specific heat at constant pressure to specific heat at constant volume is known as specific heat index. It is denoted by γ.

$$\gamma = C_p/C_v$$

2.8 DERIVATION OF SPECIFIC HEATS WITH CHARISTICS GAS CONSTANT/ RELATIONSHIP BETWEEN C_P, C_V AND R

Let us consider m kg of a gas enclosed in a container and is being heated at constant pressure.

Let T_1 = Initial temperature of the gas,
T_2 = Final temperature of the gas,
V_1= Initial volume of gas,
V_2 = Final volume of gas,

C_p = Specific heat at constant pressure,

C_v = Specific heat at constant volume,

P = Absolute constant pressure.

We know that heat supplied to the gas at constant pressure,

$Q = mC_p (T_2 - T_1)$ ………… (i)

We also know that a part of this heat is utilisec in doing external work, while the remaining part of heat is used in increasing the internal energy of gas.

i.e. $Q = W + dU$ ……………….(ii)

now heat utilised for external work,

$W = P(V_2 – V_1)$ ……………………(iii)

And increase in internal energy

$dU = mC_v (T_2 – T_1)$ …………………(iv)

Putting the values of W and dU in equation (ii)

$Q = P(V_2 - V_1) + mC_v(T_2 – T_1)$ ……………………… (v)

Using characteristic gas equation, we have

$PV_1 = mRT_1$ (For initial condition)

$PV_2 = mRT_2$ (For final condition)

$$P (V_2 – V_1) = mR (T_2 – T_1)$$

Putting the value of P (V2 – V1) from equation (vi) in equation (v), we get

$Q = mR(T_2 – T_1) + mC_v(T_2 – T_1)$

Now putting the value of Q from equation (i) in above equation, we get

$mC_p (T_2 – T_1) = mR(T_2 – T_1) + mC_v(T_2 – T_1)$

or $C_p = R + C_v$

or $C_p - C_v = R$

The equation may be written as

$$C_V \left[\frac{Cp}{Cv} - 1\right] = R$$

$C_v(\gamma – 1) = R$

$C_v = \frac{R}{\gamma - 1}$

The value of r in S.I. unit is taken as 287 J/kg K

The equation may also be written as

$C_p = C_v + R$

Dividing both sides by C_v , we get

$$\frac{Cp}{Cv} = 1 + \frac{R}{Cv}$$

$$\gamma = 1 + \frac{R}{Cv}$$

CHAPTER 3
THERMODYNAMIC PROCESSES

3.1 INTRODUCTION

When the system changes from one thermodynamic state to the final thermodynamic state due to change in pressure, temperature, volume etc, the system is said to have undergone thermodynamic process. The various types of thermodynamic processes are: isothermal process, adiabatic process, isochoric process, isobaric process and reversible process.

3.2 TYPES OF THERMODYNAMIC PROCESSES

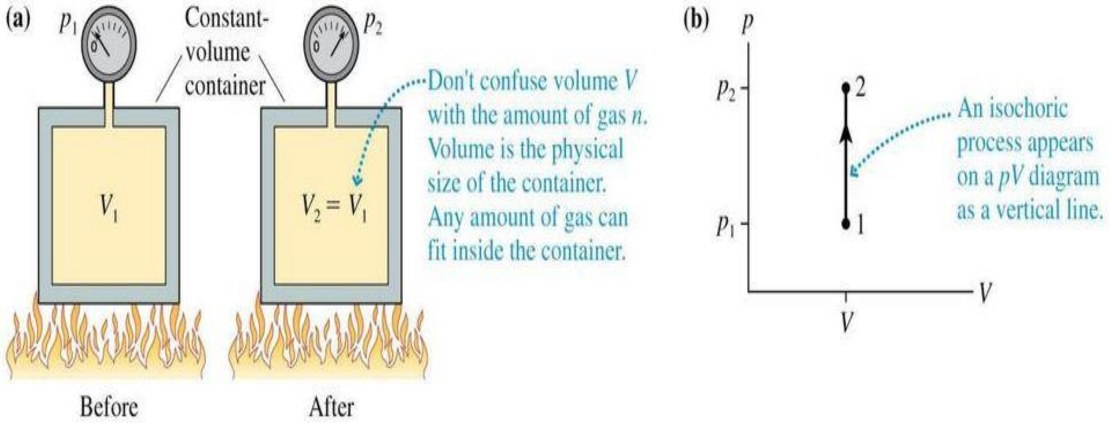
The important thermodynamic processes are:

A. Reversible non-flow processes

1. Isochoric process (Constant volume process)
2. Isobaric process (Constant pressure process)
3. Isothermal process (Constant temperature process)
4. Adiabatic process
5. Hyperbolic process
6. Polytropic process
7. Throttling process

3.2.1 Isochoric process (Constant volume process)

In this process the volume of system remains constant. The main characteristic of this process is that the displacement work is eliminated. An example of this process is the heating or cooling of a gas stored in a rigid cylinder. Since the volume of the gas does not change, no external work is done, and work transferred W is zero.



Therefore from 1st law of thermodynamics for a constant volume process:

$$Q_{1-2} - W_{1-2} = U_2 - U_1$$

But, $W_{1-2} = \int_1^2 PdV = U_2 - U_1$ ………… (dV = 0)

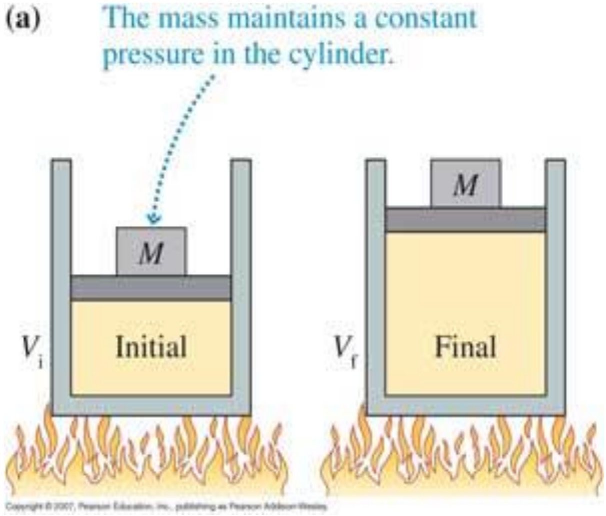
$$Q_{1-2} = U_2 - U_1$$

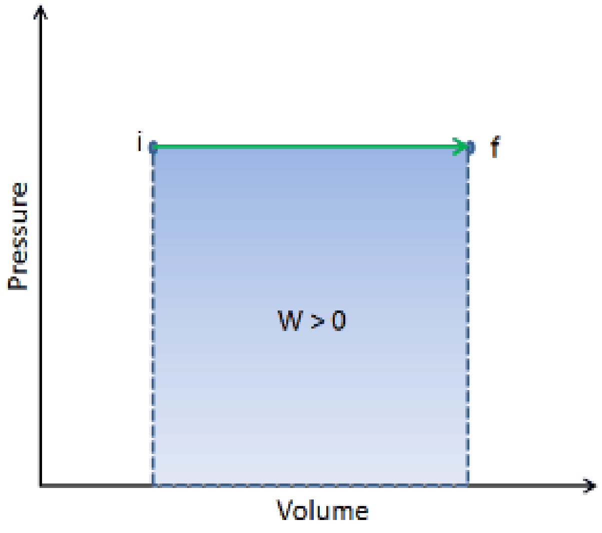
$$Q_{1-2} = mC_v (T_2 - T_1)$$

Thus, during a constant volume process, the heat transfer equals the change in internal energy of the system.

3.2.2 Isobaric process (Constant pressure process)

The process, during which the pressure of the system remains constant, is called as isobaric process. If the temperature of a gas is increased by the addition of heat while the gas is allowed to expand so that its pressure is kept constant, the volume of the gas will be increase in accordance with Charles law. Since the volume of the gas increases during the process, work is done by the gas at the same time that its internal energy also changes. Therefore for constant pressure process, assuming constant specific heats and ideal gas behaviour,





If the work is carried out quasi-statically,

$$\int_1^2 \delta W = \int_1^2 P\,dV$$

Then, from first law of thermodynamics,

$$\int_1^2 \delta Q - \int_1^2 \delta W = \int_1^2 dU$$

Or

$$\int_1^2 \delta Q = \int_1^2 \delta W + \int_1^2 dU$$

$$= \int_1^2 P\,dV + \int_1^2 dU$$

$$= \int_1^2 d(U + PV)$$

$$\int_1^2 \delta Q = \int_1^2 dH$$

Also $$\int_1^2 \delta Q = \int_1^2 mC_P dT$$

Or $$Q_{1-2} = mC_P (T_2 - T_1)$$

Thus, the heat supplied at constant pressure is equal to change in enthalpy of the system.

3.2.3 Isothermal process (Constant temperature process)

According to Boyle's law, when a gas is compressed or expanded at constant temperature, the pressure will vary inversely with the volume. Since the gas does work as it expands, if the temperature is to remain constant, energy to do the work must be supplied from an external source. When a gas is compressed, work is done on the gas and if the gas is not cooled during the process the internal energy of the gas will increase by an amount equal to the work of compression. Therefore if the temperature of the gas is to remain constant during the process gas must reject heat to the surroundings. Since there is no temperature increase in the system change in internal energy becomes zero. And the amount of work done will be the amount of heat supplied.

From first law of thermodynamics,

$$\delta Q - \delta W = dU$$

But $$dU = mC_V dT$$

Now as $$dT = 0$$

$$dU = 0$$

$$\delta Q - \delta W = 0$$

Or $$\delta Q = \delta W$$

For quasi-static process, $\int_1^2 \delta W = \int_1^2 PdV$

Or $W_{1-2} = \int_1^2 PdV = \int_1^2 \frac{PVdV}{V}$

Or $Q_{1-2} = PV\log_e\left(\frac{V_2}{V_1}\right)$

Or $Q_{1-2} = P_1V_1\log_e\left(\frac{V_2}{V_1}\right)$

Or $Q_{1-2} = mRT_1\log_e\left(\frac{V_2}{V_1}\right)$

Hence, the heat supplied during isothermal process is equivalent to non-flow work during the process.

3.2.4 Adiabatic process

The process during which work is done and no heat is transferred across the system boundary is known as adiabatic process.

Heat transferred, $Q_{1-2} = 0$

From first law of thermodynamics,

$Q_{1-2} - W_{1-2} = U_1 - U_2$

Or $Q_{1-2} - W_{1-2} = \Delta U$ ……………….. $Q_{1-2} = 0$

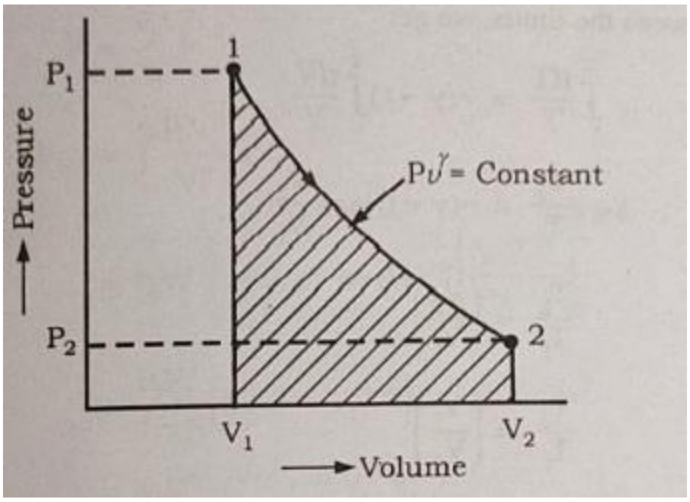
Or $-W_{1-2} = \Delta U$ ……………….. (i)

Work done = Change in internal energy

For perfect gases, we know that

$\Delta U = m \times C_v \times (T_2 - T_1)$ ………………… (ii)

Also $W_{1-2} = \int_1^2 PdV$ ………………... (iii)



Putting the values of ΔU and W1-2 from equations (ii) and (iii) in equation (i), we get

$$-\int_{1}^{2} P\,dV = m.C_V\,(T_2 - T_1)$$

Or

$$P\,dV = -\,m.\,C_V\,dT$$

………. (iv)

But

$$PV = mRT$$

Or

$$P = \frac{mRT}{V}$$

……….. (v)

Putting the value of P from equation (v) in equation (iv), we get

$$\frac{mRT}{V}.dV = -\,m.C_V.dT$$

Or

$$\frac{dT}{T} = \frac{-R}{C_V} \times \frac{dV}{V}$$

……. (vi)

Now

$$R = C_P - C_V$$

$$\frac{R}{C_V} = \frac{C_P - C_V}{C_V}$$

$$= \frac{C_P}{C_V} - 1$$

$$= \gamma - 1 \qquad \text{………. (vii)}$$

Putting the value of R/C_v from (vii) in equation (vi), we get

$$\frac{dT}{T} = -(\gamma - 1).\frac{dV}{V}$$

Integrating between the limits, we get

$$\int_1^2 \frac{dT}{T} = -(\gamma - 1)\int_1^2 \frac{dV}{V}$$

$$\log e\frac{T_2}{T_1} = -(\gamma - 1)\log e\frac{V_2}{V_1}$$

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

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

$$TV^{\gamma-1} = \text{Constant}$$

$$\frac{V_1}{V_2} = \frac{P_2T_1}{P_1T_2}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \times \frac{T_1}{T_2}\right)^{(\gamma-1)}$$

$$\frac{T_2}{T_1} \times \left(\frac{T_2}{T_1}\right)^{\gamma-1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1}$$

$$\left(\frac{T_2}{T_1}\right)^{\gamma} = \left(\frac{P_2}{P_1}\right)^{\gamma-1}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

$$PV^{\gamma} = \text{Constant}$$

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

$$PV^{\gamma} = P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

$$P = \frac{P_1V_1^{\gamma}}{V^{\gamma}}$$

$$W_{1\text{-}2} = \int_1^2 \frac{P_1V_1^{\gamma}}{V^{\gamma}}\,dV$$

$$= P_1V_1^{\gamma}\int_1^2 V^{-\gamma}.dV = P_1V_1^{\gamma}\left[\frac{V^{-\gamma+1}}{-\gamma+1}\right]_1^2$$

$$= \frac{P_1V_1^{\gamma}}{1-\gamma}\left[V_2^{1-\gamma} - V_1^{1-\gamma}\right]$$

$$= \frac{P_1V_1^{\gamma}.V_2^{1-\gamma} - P_1V_1^{\gamma}.V_1^{1-\gamma}}{1-\gamma}$$

$$= \frac{P_2V_2 - P_1V_1}{1-\gamma} \qquad \left(\because\ P_1V_1^{\gamma} = P_2V_2^{\gamma}\right)$$

$$= \frac{P_1V_1 - P_2V_2}{\gamma-1}$$

$$W_{1\text{-}2} = \frac{mR(T_1 - T_2)}{\gamma-1}$$

It should be noted that during reversible adiabatic process, entropy remains constant, so the process is also known as isentropic process.

Condition for isentropic process:

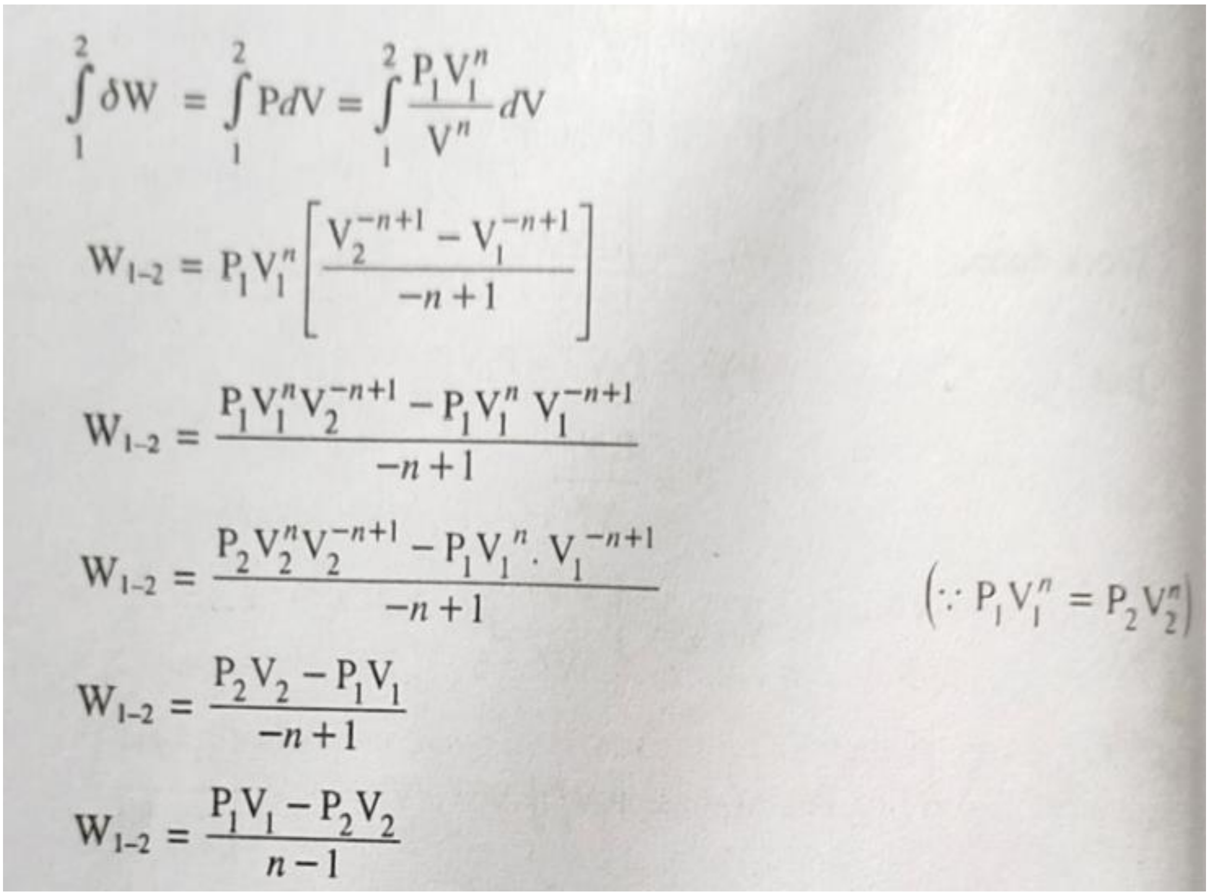
1. The process should be frictionless.
2. No heat should be transferred.
3. Work should be done by the gas or on the gas.
4. In real practice, isentropic process is not possible.

3.2.5 Isentropic Process

If an adiabatic process is reversible then it is called Isentropic process i.e., reversible adiabatic process is known as isentropic process. For an adiabatic process to qualify as isentropic process, then it should be frictionless. All the other properties of this process are same as that of adiabatic process.

3.2.6 Polytropic process

It is found that in actual practice many processes approximate to a reversible process of the PV^n = Constant, where n is called polytropic index. Both vapours and perfect gases follow this type of process closely. Work done during the process from state 1 to state 2 by system,



$$\int_1^2 \delta W = \int_1^2 P dV = \int_1^2 \frac{P_1V_1^n}{V^n} dV$$

$$W_{1-2} = P_1V_1^n \left[\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1}\right]$$

$$W_{1-2} = \frac{P_1V_1^nV_2^{-n+1} - P_1V_1^n\ V_1^{-n+1}}{-n+1}$$

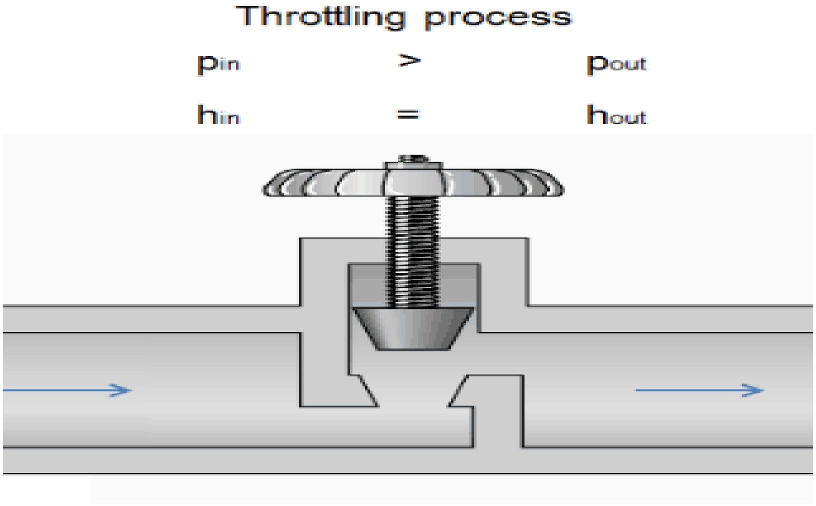
$$W_{1-2} = \frac{P_2V_2^nV_2^{-n+1} - P_1V_1^n . V_1^{-n+1}}{-n+1} \qquad (\because P_1V_1^n = P_2V_2^n)$$

$$W_{1-2} = \frac{P_2V_2 - P_1V_1}{-n+1}$$

$$W_{1-2} = \frac{P_1V_1 - P_2V_2}{n-1}$$

3.2.7 Throttling process

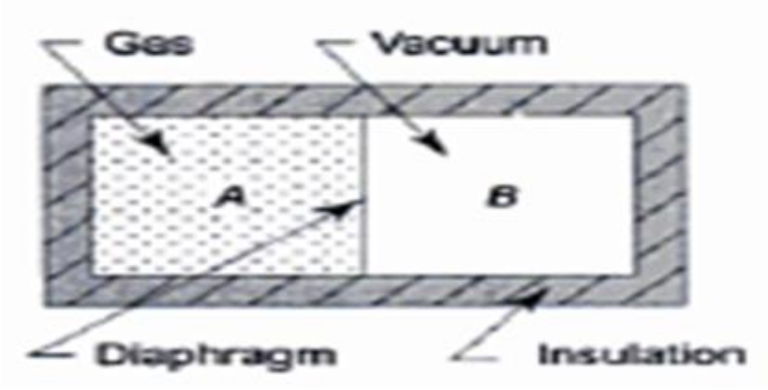
The throttling process is an irreversible steady flow expansion process in which a perfect gas is expanded through an orifice of minute dimensions such as a narrow throat or as lightly opened valve.



Due to fall in pressure during expansion, the gas should come out with a large velocity, but due to high frictional resistance between the gas and the walls of the aperture, there is no considerable change in velocity. The kinetic energy of the gas is converted into heat which is utilized in warming the gas to its initial temperature. Since no heat is supplied or rejected during the throttling process and also no work is done. There is no change in enthalpy from one state to another, $h_1 = h_2$; no work is done, $W = 0$; and the process is adiabatic, $Q = 0$.

3.2.8 Free expansion process

The expansion of gas in perfect vacuum is called free expansion. Consider a properly insulated cylinder with a partition and stopper. Now place some gas on one side and evacuate other side. When stopper is removed the gas expands freely to the other side of cylinder. This process is called free expansion or irreversible isothermal process.



Since it is properly insulated no heats enters or leave the cylinder (adiabatic) and temperature of gas remains constant i.e., isothermal. The matter inside cylinder does not cross the system boundaries (walls of cylinder) hence work done is 0. Since temperature is constant, there is no change in internal energy of system.

$$\delta Q - \delta W = dU$$

Since, $dU = 0$, Thus, internal energy of system remains constant.

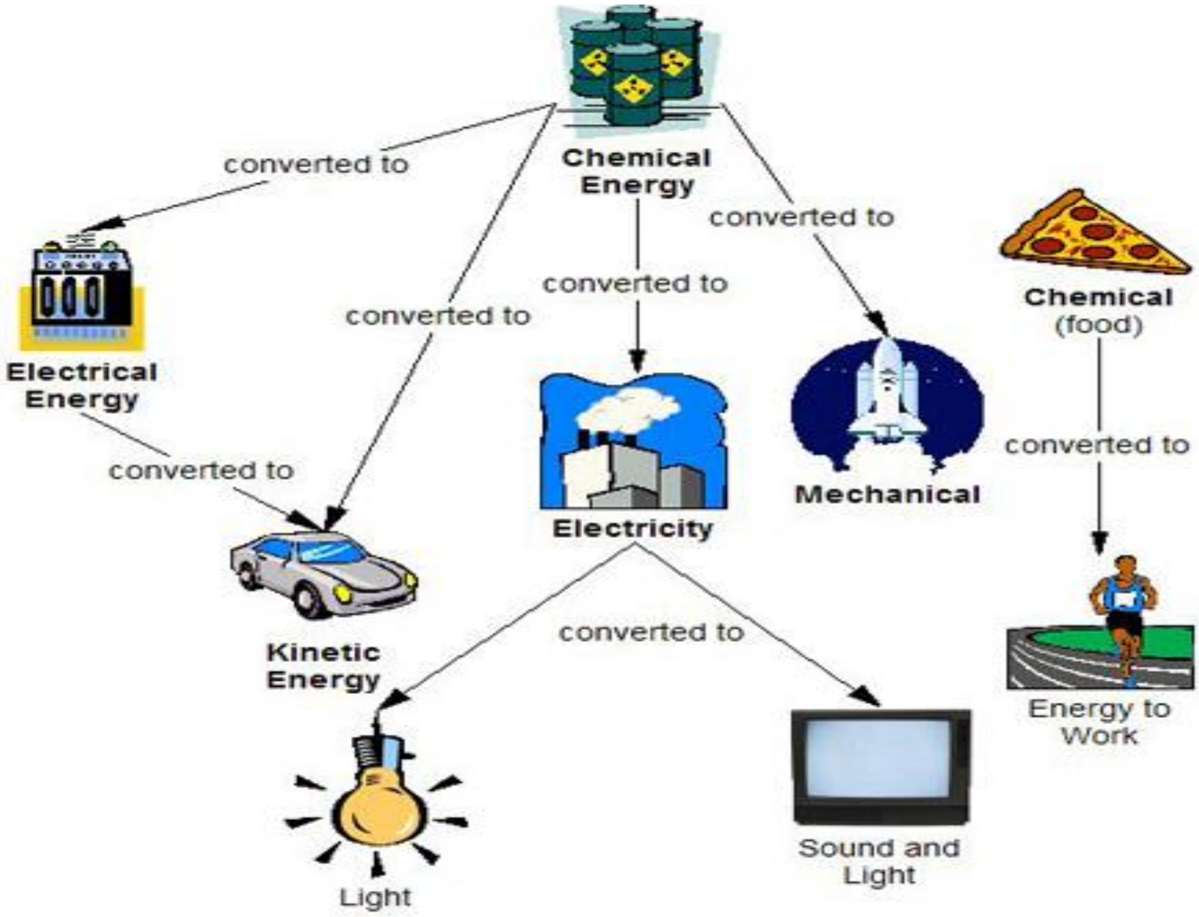
$$H = U + PV$$

CHAPTER 4

LAWS OF THERMODYNAMICS

4.1 LAW OF CONSERVATION OF ENERGY

The law of conservation of energy states that energy can neither be created nor destroyed - only converted from one form of energy to another. This means that a system always has the same amount of energy, unless it's added from the outside. Some examples of conservation of energy are as follow:



1. Conversion of electrical energy into heat energy by flowing of current through a resistance.
2. Conservation of water energy into heat energy during power generation in a hydroelectric power plant.

4.2 FIRST LAW OF THERMODYNAMICS (JOULE's EXPERIMENT)

It is special case of law of conservation of energy and may be explained as follow for the following systems:

4.2.1 First law for a closed system undergoing a cycle

Let us consider a closed system which consist of a known mass of water, (m) contained in an adiabatic vessel having a thermometer and a paddle wheel as shown in fig.

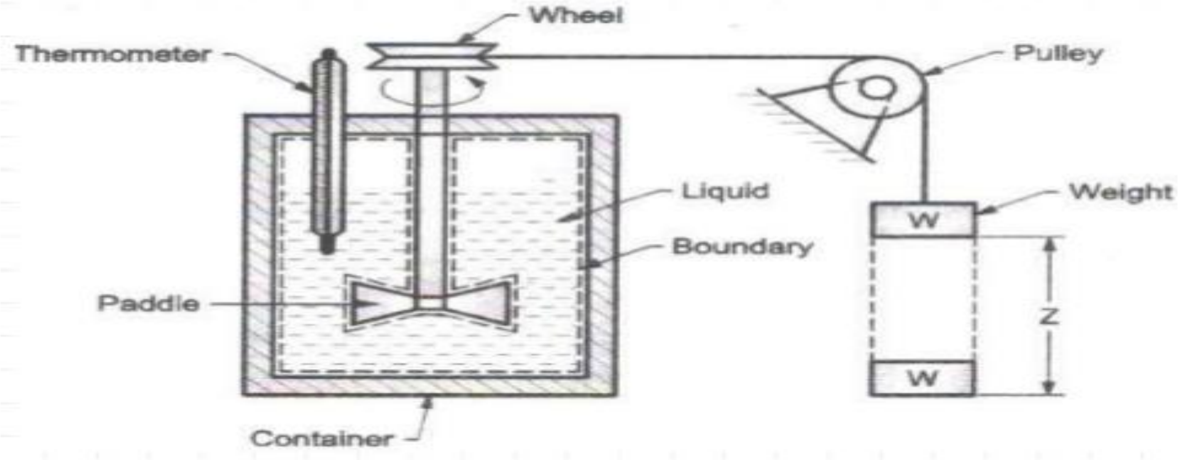


Fig. 4.1 Joule experiment apparatus

Let a certain amount of work (W_{1-2}) be done upon the system by the paddle wheel. The quantity of work can be measured by the fall of weight which derives the paddle wheel through a pulley. The system initially was at temperature (T_1), the same as that of the atmosphere and after the work transfer let the temperature rise to (T_2). The process 1-2 undergone by the system is shown in the figure 8, in generalized thermodynamic coordinates X, Y.

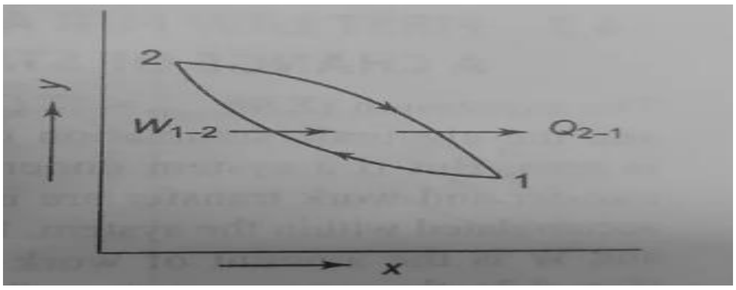


Fig. 4.2 Cyclic process

The system and the surrounding interact by heat transfer till the system returns to the original temperature (T_1), attaining the condition of thermal equilibrium with the atmosphere. The amount of heat transfer (Q_{2-1}) from the system during the process (2-1) shown in the figure above, can be estimated from,

$$\mathbf{Q_{2-1} = mC_p (T_2 - T_1)}$$

The systems thus execute a cycle, which consist of a definite amount of work input (W_{1-2}) to the system followed by the transfer of an amount of heat (Q_{2-1}) from the system.

$$(\sum W)_{\text{cycle}} = J (\sum Q)_{\text{cycle}}$$

The work (W_{1-2}) is always proportional to the heat (Q_{2-1}) and constant of proportionality is called the Joule's equivalent or mechanical equivalent of heat. If the cycle involves many more heat and work quantities, the same result will be found,

$$\oint dW = \mathrm{J} \oint dQ$$

Where,

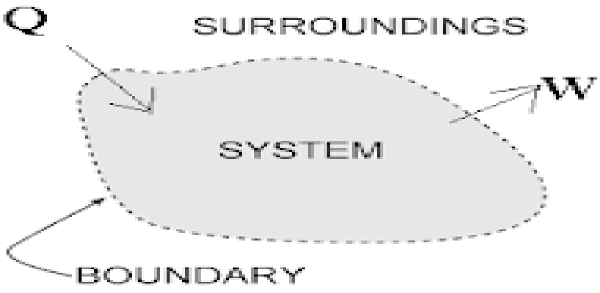
J = Joule's equivalent.

$\oint$ = Denotes the cyclic integral for the closed path.

This is the first law for a closed system undergoing a cycle. It is accepted as a general law of nature, since no violation of it has ever been demonstrated. In this, the algebraic summation of all energy transfer i.e. heat energy transfer and work energy transfer across the system boundaries will be zero.

4.2.2 First law for a closed system undergoing a change of state

Let we have one closed system which is undergoing a change of state and energies i.e. work energy and heat energy both are crossing the system boundaries. Net energy will be stored within the system in the form of internal energy. The Q heat energy enters the system from surrounding and work energy W leave the system or we can also say that system is doing work W on the surrounding by taking Q amount of heat energy from the surrounding.

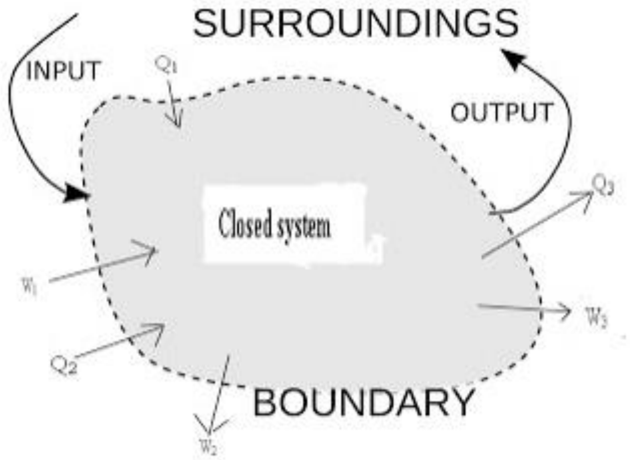


(Q-W) will be the net energy and it will be accumulated within the system and hence there will be increment in internal energy of the system as (Q-W) amount of energy will be stored within the system during this process. Therefore according to the first law of thermodynamics, we have following equation for above thermodynamic process where system is under a change of state.

$$Q - W = \Delta U$$

Where, ΔU is increase in internal energy of the system during the process.

Let we have one system where multiple energies are crossing the system boundary in a process as shown in figure, “Sign convention used for heat and work energy transfer across the system boundary “and we will write here the equation of energy transfer across the system boundary according to the first law of thermodynamics for this process.



$$Q_1 + Q_2 - Q_3 - W_1 + W_2 + W_3 = \Delta U$$

This equation shows the change in internal energy or change of system energy.

4.2.3 Limitations of First law first law of thermodynamics (Joule's experiment)

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.

4.3 STEADY FLOW ENERGY EQUATION

Before going for the energy equation, let us first discuss the conditions which must be satisfied for the steady flow process.

1. The mass flow through the system remains constant.
2. Fluid is uniform in composition.
3. The only interaction between the system and surroundings are work and heat.
4. The state of fluid at any point remains constant with time.
5. In the analysis only potential, kinetic and flow energies are considered.

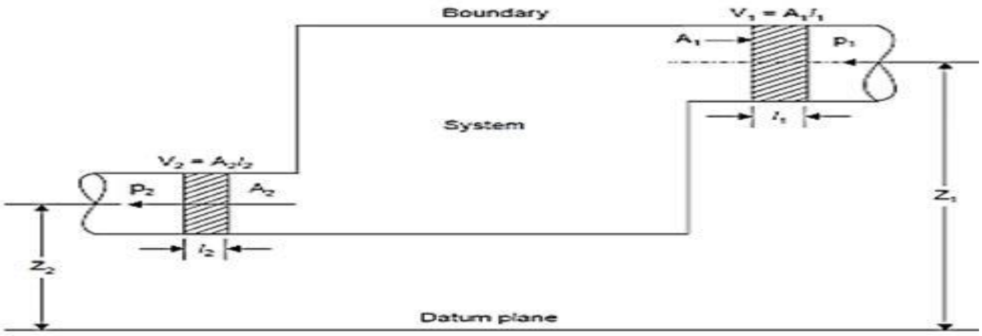


Fig. 4.3 Steady flow process

Let P1, P2 = Pressure of working substance at inlet and outlet of system,

Z1, Z2 = Datum height at inlet and outlet,

C1, C2 = Velocity of working substance at inlet and outlet,

Q = Heat supplied to the system,

W = Work delivered by the system,

V1, V2 = Volume of working substance entering and leaving the system,

U1, U2 = Internal energy of working substance at inlet and outlet,

m = Mass of working substance

We know that energy entering the system is

$$E_{entering} = U_1 + \frac{mC_1^2}{2} + mZ_1 g + P_1 V_1 + Q$$

Similarly, energy leaving the system is

$$E_{outlet} = U_2 + \frac{mC_2^2}{2} + mZ_2g + P_2V_2 + W$$

From assumption

$$E_{entering} = E_{outet}$$

$$U_1 + \frac{mV_1^2}{2} + mZ_1g + P_1V_1 + Q = U_2 + \frac{mC_2^2}{2} + mZ_2g + P_2V_2 + W$$

Also, we know that,

$$H_1 = U_1 + P_1V_1$$
$$H_2 = U_2 + P_2V_2$$

And

$$H_1 + \frac{mC_1^2}{2} + mZ_1g + Q = H_2 + \frac{mC_2^2}{2} + mZ_2g + W$$

The above equation is known as steady flow energy equation. Mass flow rate (m) of the working substance in a steady flow is given by

$$\dot{m} = \frac{A_1V_1}{v_1} = \frac{A_2V_2}{v_2}$$

4.4 APPLICATIONS OF GENERAL STEADY FLOW EQUATION

Some of the important applications of general steady flow equations are as follows:

1. Turbine

A turbine is a rotary steady state steady flow machine whose purpose is the production of shaft power at the expense of the pressure of the working fluid. Two general classes of turbines are steam and gas turbines depending on the working substance used. Usually, changes in potential energy are negligible, as is the inlet kinetic energy. Often the exit kinetic energy is neglected (if in a problem, the flow velocities are specified, the kinetic energy term should be included). Normally, the process in the turbine is adiabatic and the work output reduces to decrease in enthalpy from the inlet to exit states.

$$H_1 + \frac{mC_1^2}{2} + mZ_1 g = H_2 + \frac{mC_2^2}{2} + mZ_2 g + W$$

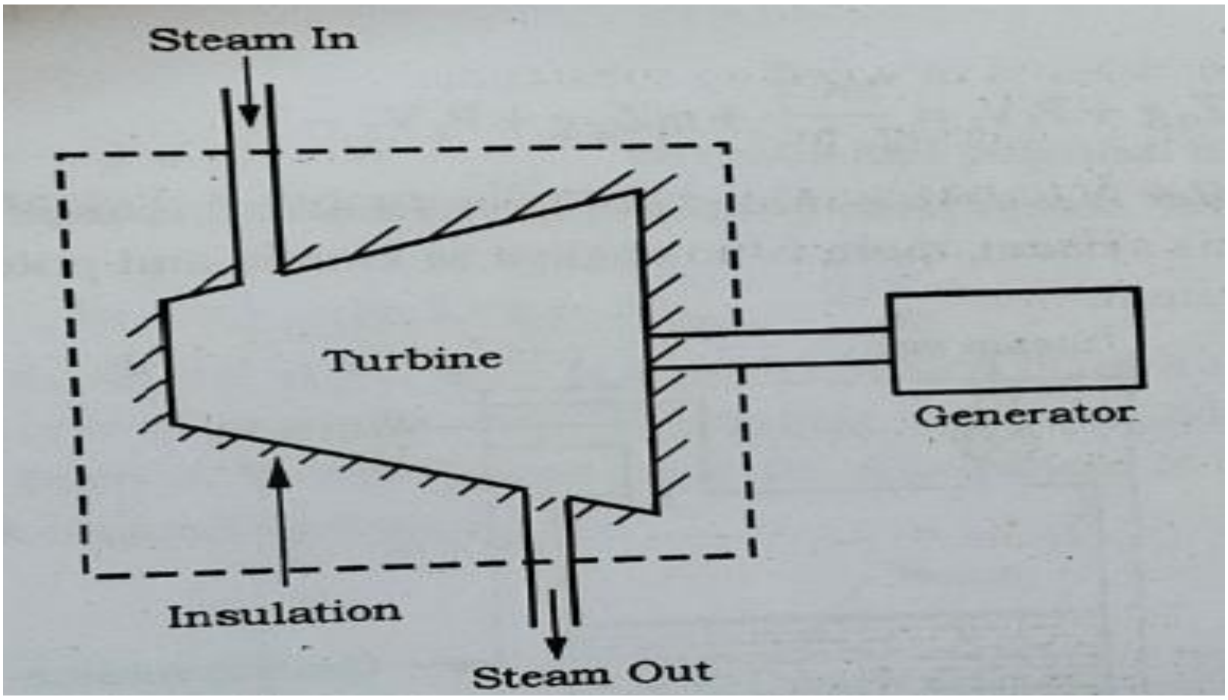


Fig. 4.4 Turbine

$$\mathbf{H_1 = H_2 + W}$$

$$\mathbf{W = H_1 - H_2}$$

This shows that the work done by the system is due to the decrease in enthalpy of working substance.

2. Pump

A pump is a device which lifts the water from lower level and delivers it to higher level as shown in fig. the pump is run by an external device, therefore work is –ve in this case. Also the change in internal energy of water is zero i.e. $Q = 0$ and U_1-U_2 = 0.

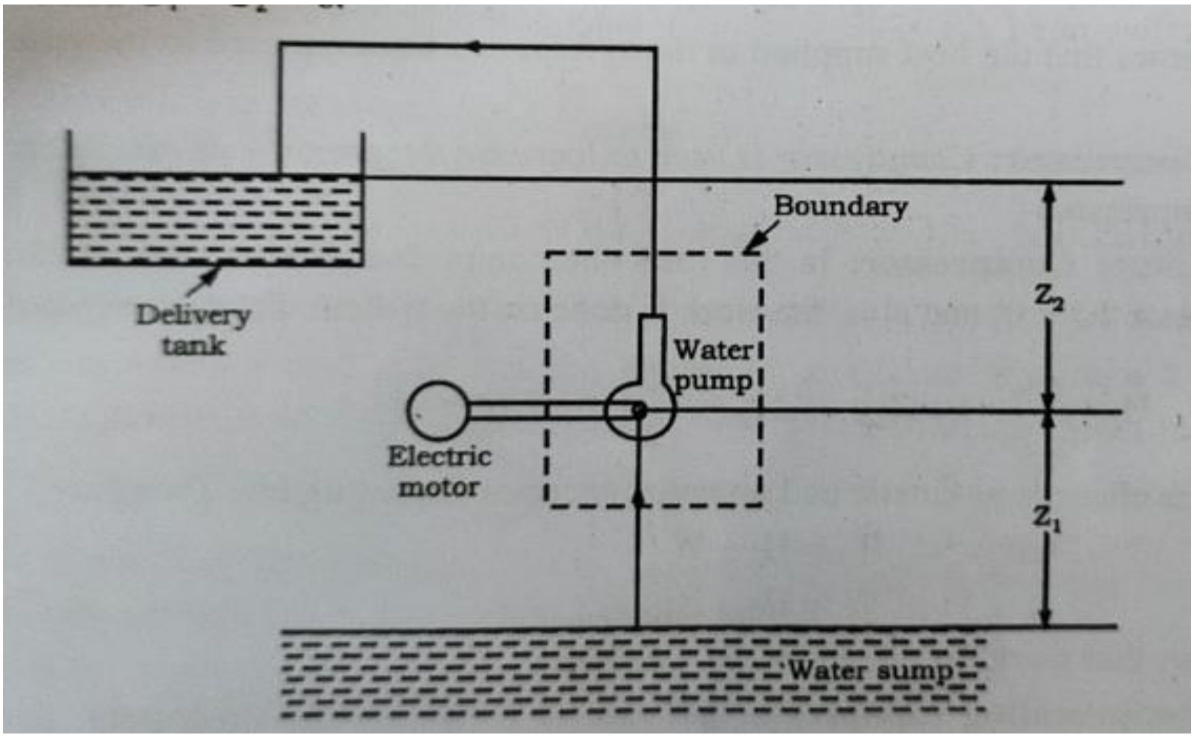


Fig. 4.5 Pump

3. Boiler

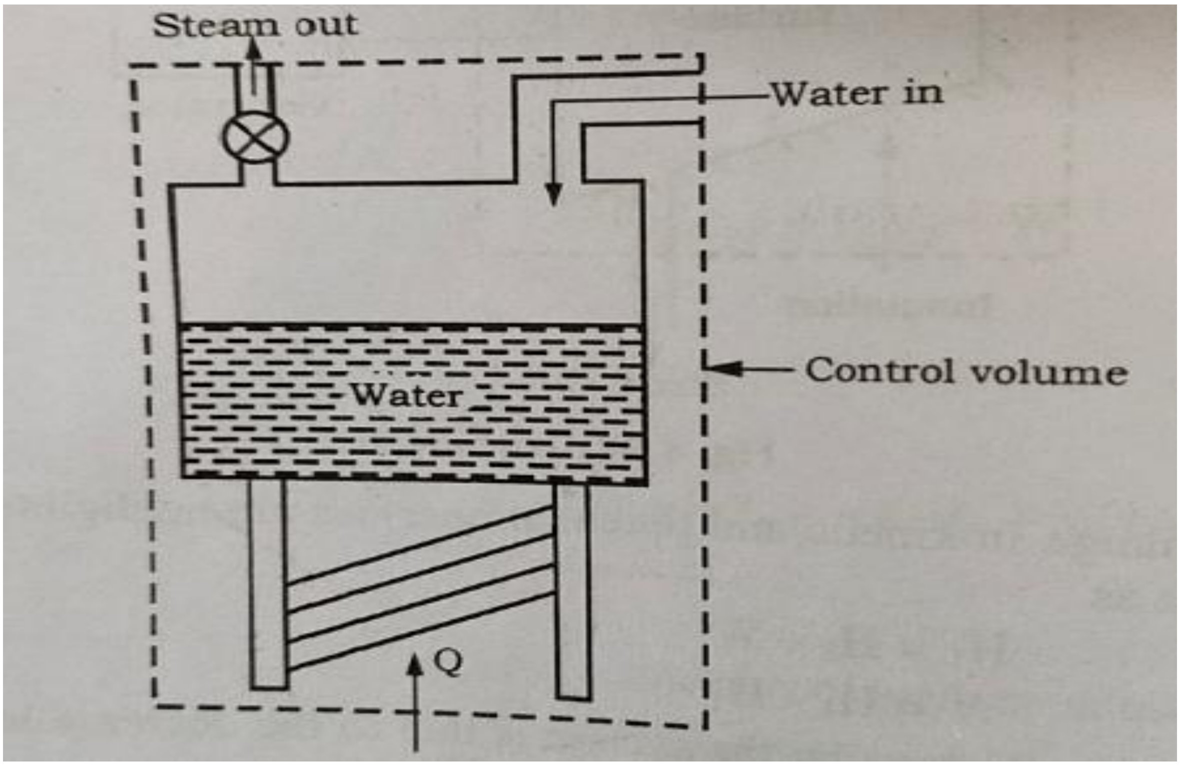


Fig. 4.6 Boiler

A boiler is a device shown in fig which is used to generate the steam after heating the water. In this system, there is no change in kinetic energy and potential energy. Also there is no work done by system.

Therefore, from general energy equation,

$$\mathbf{H_1 + Q = H_2}$$

$$\mathbf{Q = H_2 - H_1}$$

This show that the heat supplied to the system in a boiler is used to increase the enthalpy of the system.

4. Compressor

Compressor is used to increase the pressure of air. There are mainly two types of compressors:

a) Rotary compressor

In this case, the compressor is insulated, so that no transfer of heat takes place (Q = 0) and also, the work is done on the system. From energy equation

$$H_1 + \frac{mC_1^2}{2} + mZ_1 g = H_2 + \frac{mC_2^2}{2} + mZ_2 g - W$$

Also the change in K.E. and P.E. are negligible.

$$\mathbf{H_1 = H_2 - W}$$

$$\mathbf{W = H_2 - H_1}$$

It shows that work is done to increase enthalpy.

b) Reciprocating compressor

The rate of flow is low as compared to rotary compressor, so there is large area in contact with surroundings. Amount of heat transfer in appreciable and cannot be ignored.

Therefore,

$$\mathbf{H_1 - Q = H_2 - W}$$

The –ve sign of Q and W indicate that in reciprocating compressor, heat is rejected and work is done on the system.

5. Nozzle

It is a device which is used to increase the velocity of working substance at the cost of pressure drop. The nozzle is considered to be insulated so that there is no transfer of heat from or to the system (Q = 0). Also there is no change in potential energy and no external work is done by the system. From general energy equation,

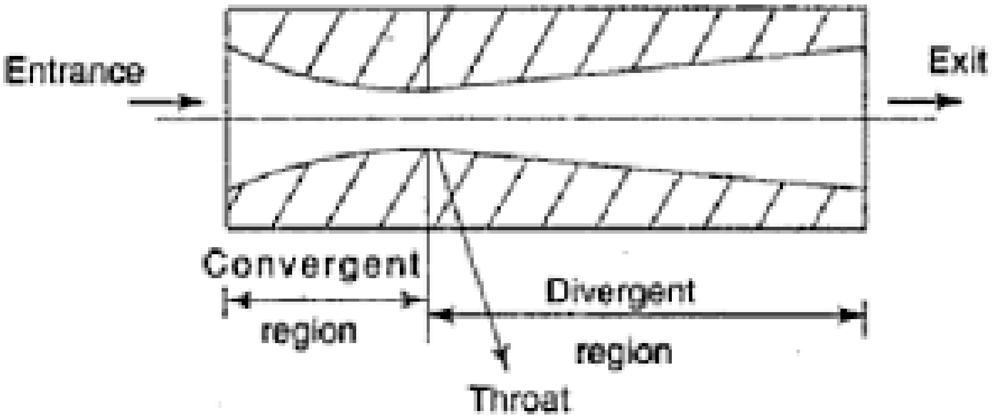


Fig. 4.7 Nozzle

$$H_1 + \frac{mC_1^2}{2} = H_2 + \frac{mC_2^2}{2}$$

$$H_1 - H_2 = \frac{mC_2^2}{2} - \frac{mC_1^2}{2}$$

Now, C_1 is very small as compared to C_2, so C_1 may be ignored. From general energy equation,

$$C_2 = \sqrt{\frac{2(H_1 - H_2)}{m}}$$

Above relation shows that the increase in K.E. will results in decrease in enthalpy.

6. Evaporator

It is device which is used in refrigeration system. In evaporator, liquid refrigerant receives heat and leaves as vapors refrigerant. In thus system, kinetic energy and potential energy can be neglected. Also there is no work done by the system.

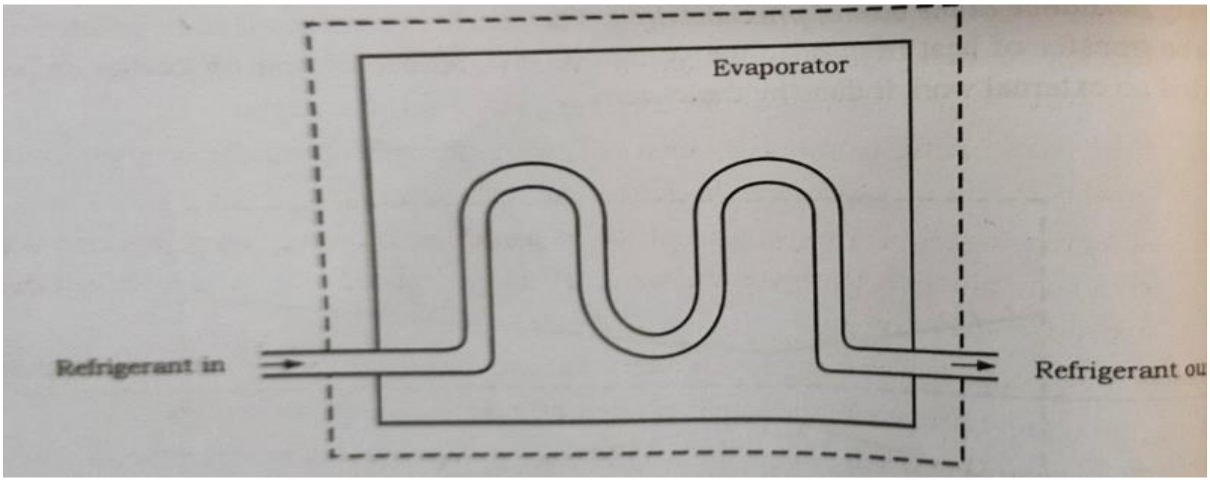


Fig. 4.8 Evaporator

$$H_1 + Q = H_2$$

$$Q = H_2 - H_1$$

4.5 HEAT SOURCE AND HEAT SINK

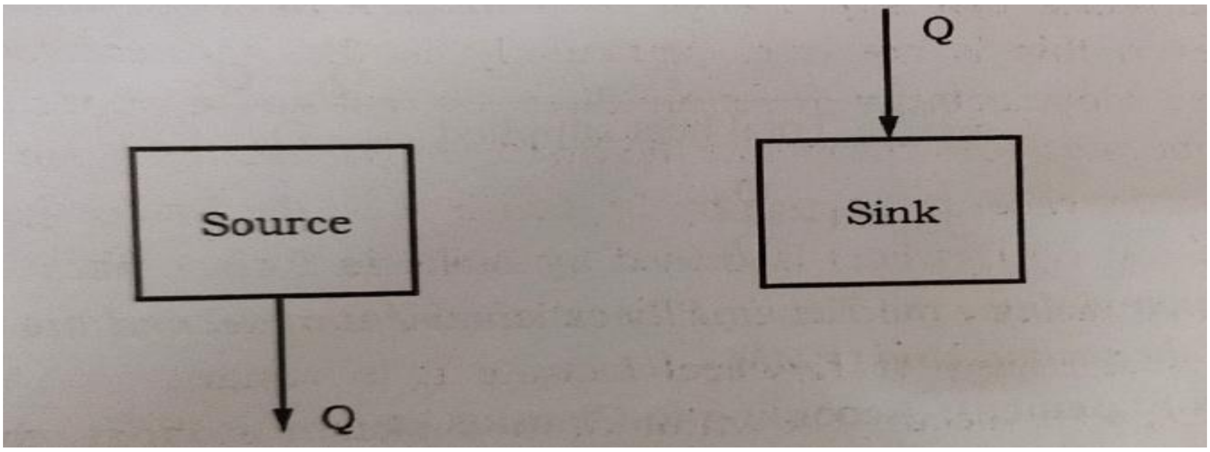


Fig. 4.9 Heat Source and heat Sink

Ideally sink and source are thermal reservoirs of infinite thermal capacities. This means you can extract (source) or reject (sink) heat from them without changing their temperature. Practically such device does not exist; these are just concepts to make study of thermodynamic systems like heat engine and refrigerator easy.

4.6 STATEMENT OF SECOND LAW OF THERMODYNAMICS

The Second Law of Thermodynamics states that the state of entropy of the entire universe, as an isolated system, will always increase over time. The second law also states that the changes in the entropy in the universe can never be negative. However, in some cases where the system is in thermodynamic equilibrium or going through a reversible process, the total entropy of a system and its surroundings remains constant. The second law is also known as the law of degradation of energy.

There are two statements on the second law of thermodynamics which are;

1. Kelvin- Plank statement
2. Clausius statement
3.

(A) Kelvin – Planck statement

It is impossible for any device that operates on a cycle, to receive heat from a single reservoir and produce a net amount of work. In other words, no heat engine converts or can convert whole of the heat energy into mechanical work and there will always be a heat rejection.

Let us assume that heat energy (Q_1) at temperature T_1 is supplied to heat engine from source and heat energy (Q_2) at temperature T_2 is rejected to the sink. Then remaining or net energy ($Q_1 - Q_2$) will be converted into mechanical work (W_{net}). The ratio of maximum mechanical work obtained to the total heat supplied to the engine is known as thermal efficiency of heat engine.

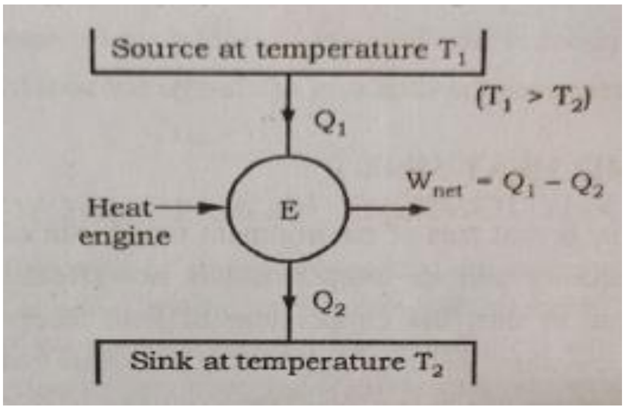


Fig. 4.10 Heat engine

$$\eta_{th} = \frac{W_{net}}{\text{Total heat supplied}} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta_{th} = 1 - \frac{Q_2}{Q_1}$$

If $Q_2 = 0$ (i.e., $W_{net} = Q_1$, or efficiency = 1), the heat engine produces work in a complete cycle by exchanging heat with only one reservoir, thus violating the Kelvin-Planck statement of second law is known as perpetual motion machine of second kind (PMM-II).

(B) Clausius statement

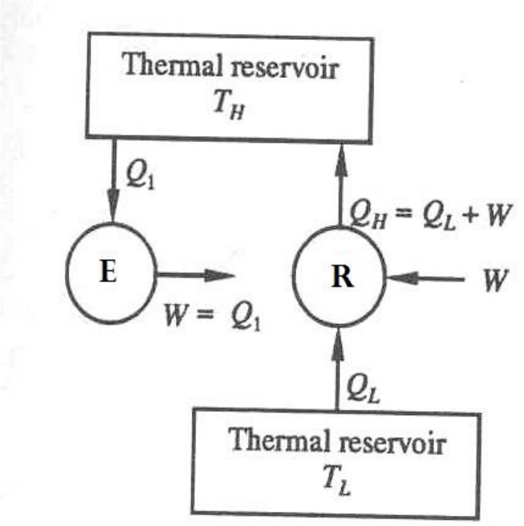
It is impossible to construct a device operating in a cycle that can transfer heat from a colder body to warmer without consuming any work. Therefore, heat cannot flow is itself from a body at a higher temperature. The applications of this law are found in a heat pump and refrigerator.

(C) Equivalency of Kelvin Planck’s and Classius statements

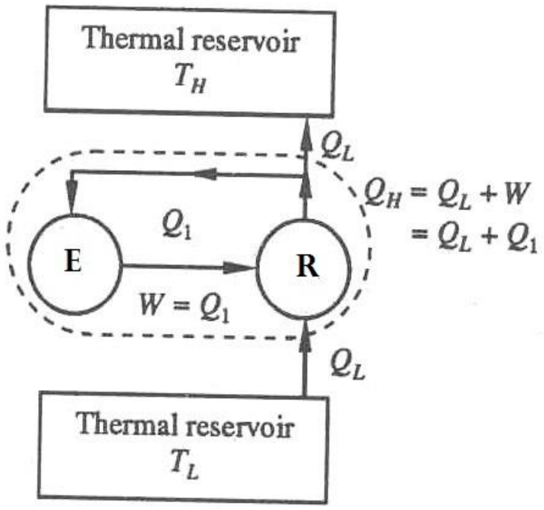
To prove that violation of the Kelvin-Planck Statement leads to a violation of the Clausius Statement, let us assume that Kelvin-Planck statement is incorrect.

Consider a cyclically working heat engine (E), which absorbs energy Q_1 as heat from a thermal reservoir at T_H. Equivalent amount of work W ($W = Q_1$) is performed.

Consider refrigerator (R) operating as a cycle, which absorbs energy Q_L as heat from a low temperature thermal reservoir at T_L and rejects energy Q_H ($Q_H = Q_L + W$). Such a device does not violate Clausius statement.

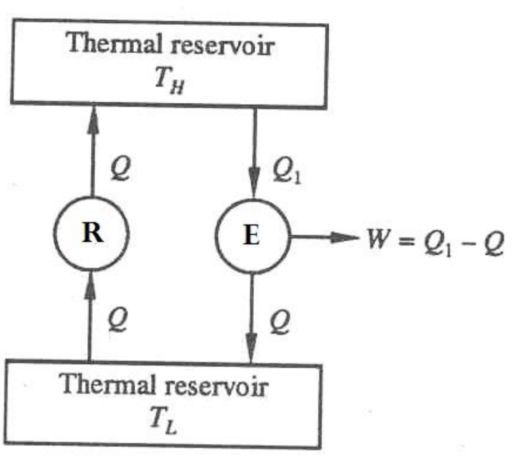


(a)

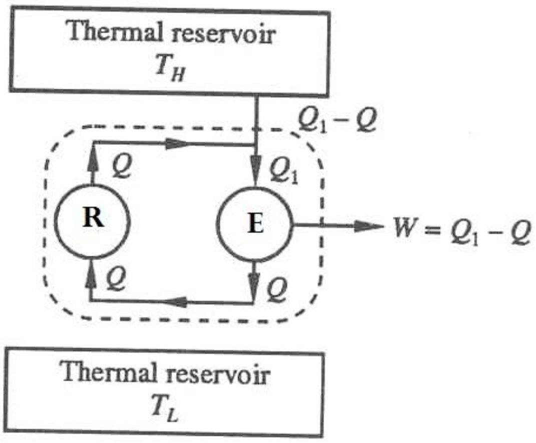


(b)

If the two devices are now combined, the combined device (enclosed by the dotted boundary) transfers heat Q_L from the low temperature reservoir at T_L to a high temperature reservoir at T_H without receiving any work from an external device, which is the violation of the Clausius statement.



(a)



(b)

Likewise let us assume that the Clausius statement is incorrect. So we have a refrigerator (R), cyclically working transferring heat Q from a low temperature reservoir at T_L to a high temperature thermal reservoir at T_H. Consider heat engine (E), which absorbs heat Q_1 from a high temperature reservoir at T_H does work W and rejects energy Q as heat tot the low temperature reservoir at T_L as shown in figure.

If the two devices are combined (shown in figure by a dotted enclosure), then the combined device receives energy (Q_1-Q) as heat from a thermal reservoir and delivers equivalent work ($W=Q_1-Q$) in violation of the Kelvin-Planck statement. Therefore violation of Clausius statement leads to the violation of the Kelvin-Planck statement. Hence, these two statements are equivalent.

(D)Heat pump: It is a device operating in cyclic process which maintains the temperature of a hot body at a temperature higher than the temperature of surroundings. Heat pump operates between atmospheric temperature and hot body temperature. Performance of a heat pump is measured by a term known as coefficient of performance which is defined as the ratio of maximum heat transfer to the amount of work done.

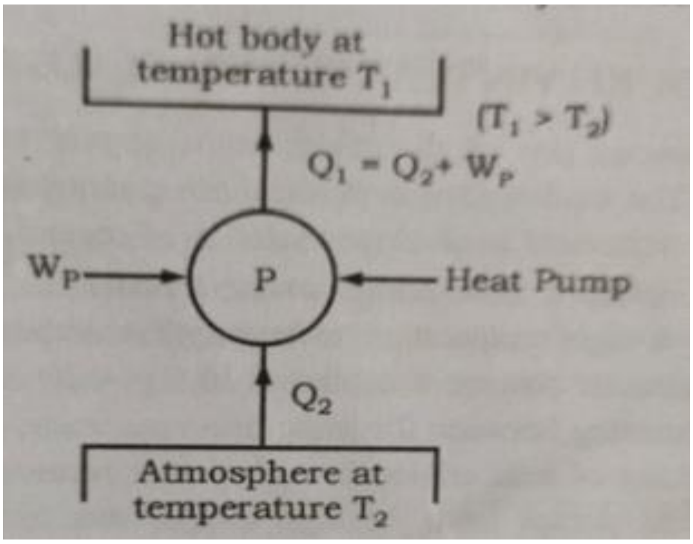


Fig.4.11 Heat pump

$$(C.O.P)_{H.P.} = \frac{Q_1}{W_P} = \frac{Q_1}{Q_1 - Q_2}$$

(D) **Refrigerator:** A refrigerator is a device operating in a cycle which maintains a body at a temperature lowers than the temperature of the surroundings. A refrigerator works between the cold body temperature and the atmospheric temperature.

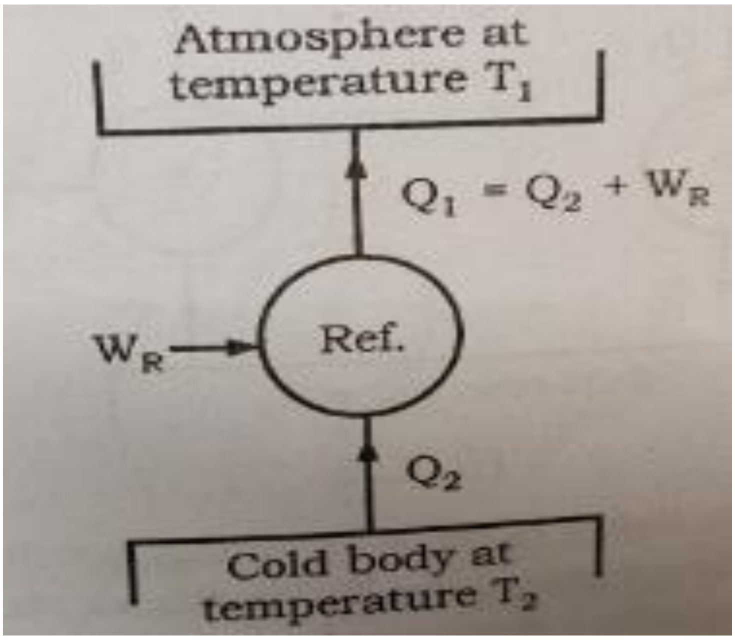
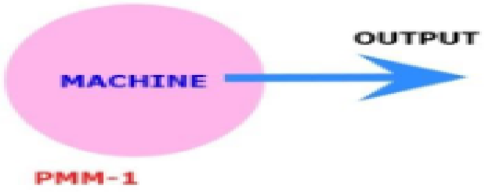


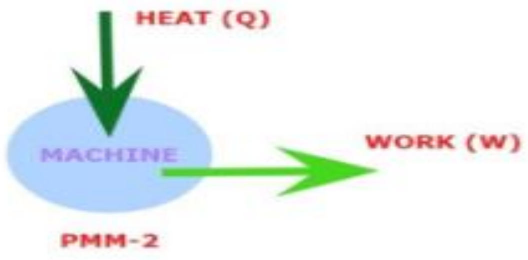
Fig. 4.12 Refrigerator

4.7 PERPETUAL MOTION MACHINE (PMM)

A device that violates the first law of thermodynamics (by creating energy) is called a Perpetual motion machine of the first kind.

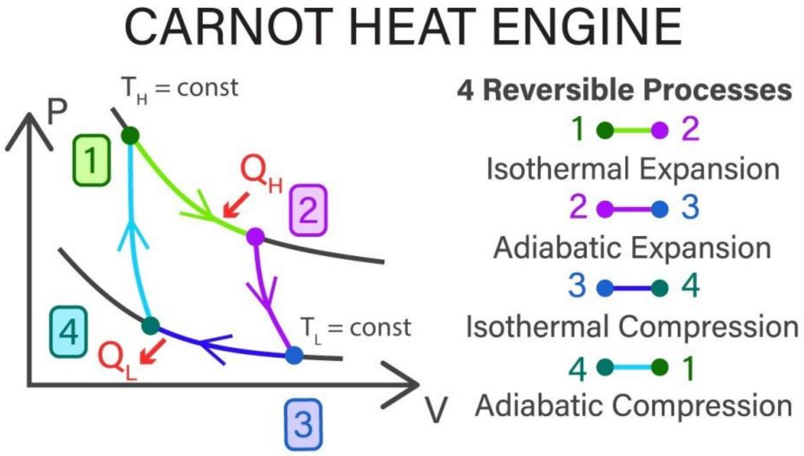


A device that violates the second law of thermodynamics is called a Perpetual motion machine of the second kind.



4.8 CARNOT ENGINE

Carnot engine is a theoretical thermodynamic cycle proposed by Leonard Carnot. It gives the estimate of the maximum possible efficiency that a heat engine during the conversion process of heat into work and conversely, working between two reservoirs, can possess. It is an idealized engine whose working is perfectly reversible. This engine uses an ideal gas as the working substance and performs a 4-stroke process to complete one cycle. The reversible cycles cannot be achieved in practice because of irreversibility's associated with real processes. But, the reversible cycles provide upper limits on the performance of real cycles.



Consider a gas in a cylinder-piston (closed system). The Carnot cycle has four processes:

1. Reversible isothermal expansion (1-2): The cylinder containing ideal gas is working substance allowed to expands slowly at this constant temperature (T_H).

2. Reversible adiabatic expansion (2-3): The cylinder-piston is now insulated (adiabatic) and gas continues to expand reversibly (slowly). So, the gas is doing work on the surroundings, and as a result of expansion the gas temperature reduces from T_H to T_L.

3. Reversible isothermal compression (3-4): The gas is allowed to exchange heat with a sink at temperature TL as the gas is being slowly compressed. So, the surroundings are doing work (reversibly) on the system and heat is transferred from the system to the surroundings (reversibly) such that the gas temperature remains constant at T_L.

4. Reversible adiabatic compression (4-1): The gas temperature is increasing from T_L to T_H as a result of compression.

$$\eta_{\text{max}} = \eta_{\text{Carnot}} = 1 - \frac{T_{\text{C}}}{T_{\text{H}}}$$

4.9 THIRD LAW OF THERMODYNAMICS

This law states, 'At absolute zero temperature, the entropy of system is zero'. Zero entropy means the absence of all molecular, atomic, nuclear and electronic disorders. It has two important consequences, it defines the sign of the entropy of any substance at temperatures above absolute zero as positive, and it provides a fixed reference point that allows us to measure the absolute entropy of any substance at any temperature.

4.10 CONCEPT OF IRREVERSIBILITY

A process is said to be reversible if both the system and the surroundings can be restored to their respective initial states, by reversing the direction of the process. A reversible process is a process that can be reversed without leaving a trace on the surroundings. Processes that are not reversible are called Irreversible processes.

Irreversibilities

The factors that cause a process to be irreversible are called irreversibilities.

1. Friction
2. Unrestrained expansion
3. Mixing of two gases
4. Heat transfer across a finite temperature difference
5. Spontaneous chemical reactions
6. Expansion or Compression with finite pressure difference
7. Mixing of matter at different states

4.11 CONCEPT OF ENTROPY

The term entropy means transformation. It is a function of quantity of heat which shows the possibility of conversion of that heat into work. As a matter of fact, it is difficult to define entropy. But change of entropy of a substance can be easily defined. In a reversible process, over a range of temperature, the increase or decrease of entropy when multiplied by the absolute temperature gives the heat absorbed or rejected by the working substance. Mathematically,

$$\boldsymbol{\delta Q = TdS}$$

Where, T = Absolute temperature, dS = Change in entropy

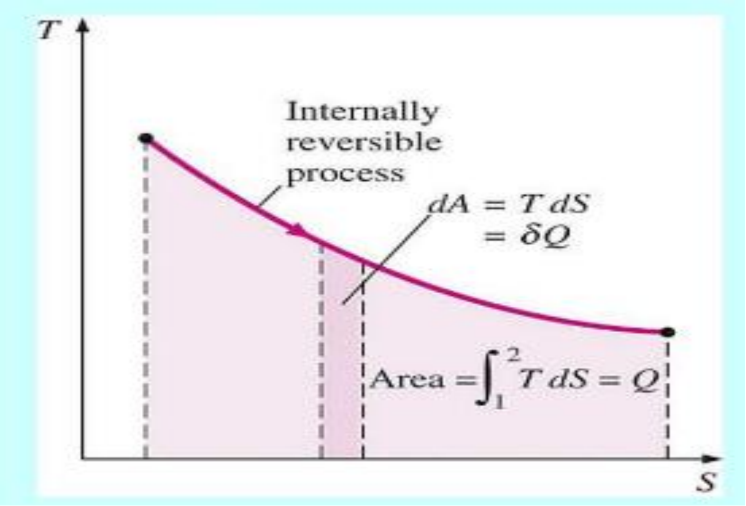


Fig. 4.13 T-S diagram

The relation between heat and entropy is given by Clausius. To prove this, let us consider the heating of a working substance by reversible process. Entropy is represented on the abscissa and absolute temperature on the ordinate. This diagram is known as temperature – entropy diagram.

$$\mathbf{dS} = \frac{\delta Q}{T}$$

Importance of entropy: The change in entropy represents the maximum amount of work done per degree drop in temperature. In other words, change in entropy may be regarded as the rate of availability or unavailability of heat for transformation into work.

CHAPTER 5

IDEAL AND REAL GASES

5.1 CONCEPT OF AN IDEAL GAS

A hypothetical gas which obeys the law Pv = RT at all temperatures and pressures is known as ideal gas.

5.2 ENTHALPY OF AN IDEAL GAS

The 'enthalpy' is defined by the relation,

$$H = U + PV$$

$$h = u + Pv$$

For unit mass,

For an ideal gas $Pv = RT$

$$h = u + (RT)_{\text{ideal gas}}$$

Since for an ideal gas u is a function of temperature, so it follows that the enthalpy is also a function of temperature alone.

5.3 SPECIFIC HEATS OF AN IDEAL GAS

The specific heat at constant volume, CV and the specific heat at constant pressure, C_P are defined as:

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

and

$$C_P = \left(\frac{\partial h}{\partial T}\right)_P$$

Since u and h of an ideal gas are functions of temperature alone, it follows that the specific heats of an ideal gas are also functions of temperature alone. Thus,

$$C_V = \left(\frac{du}{dT}\right)_{\text{Ideal gas}}$$

and $$C_P = \left(\frac{dh}{dT}\right)_{\text{Ideal gas}}$$

Since, $$h = u + (RT)_{\text{Ideal gas}}$$

∴ $$\frac{dh}{dT} = \frac{du}{dT} + (R)_{\text{Ideal gas}}$$

$$C_P = C_V + (R)_{\text{Ideal gas}}$$

Or $$C_P - C_V = (R)_{\text{Ideal gas}}$$

Further,

Where denote the molar specific heats at constant pressure and at constant volume respectively.

5.4 P-V-T SURFACE

The equation of state of a substance, whether pure or ideal, is a relationship between three variables: P, V and T. if these variable are plotted along three mutually perpendicular axes, it will result in a surface representing the equation of state graphically. Such a surface is called P-V-T surface.

5.5 P-V-T SURFACE OF AN IDEAL GAS

A portion of the P-T-V surface of an ideal gas is shown in fig. Each point on this surface represents a possible equilibrium state and line on the surface represents a quasistatic process.

5.6 TRIPLE POINT

Triple point plays a significant role in the general change of phase of a substance.

The sublimation, fusion and evaporation lines meet at point T, called triple point. The triple point may thus be defined as the point at which all three phases-solid, liquid and vapour co-exist in equilibrium. The triple point point exists in equilibrium. The triple point exists at a definite pressure and temperature. For water, triple point values are

T_{tp} = 0.01 °C and P_{tp} = 0.311kPa

5.7 REAL GAS

All gases, commonly used in engineering practice are real gases. The real gases do not obey the gas laws strictly and their equation of state is not exactly the same as that of perfect gases i.e. Pv= RT.

The experiments of Boyle's and Charle's laws were performed at relatively low pressures and temperatures. Under these conditions, most of the real gases obey Boyle's and Charle's laws quite closely.

It is possible to derive the ideal gas equation Pv = RT analytically using the kinetic theory of gases, provided the following assumptions are made:

1. The molecules are separated by large distances as compared to their own dimensions.

2. The molecules do not to exert forces on one another except they collide.

3. A finite volume of gas contains large number of molecules.

5.8 VANDER WAAL'S EQUATION OF STATE

The concept of a perfect gas which obeys the equation of state pv = RT stems from the kinetic theory of gases which makes the following assumptions about the gas molecules:

(i) The collision of molecules with one another and the walls of the container is perfectly elastic.

(ii) There is no molecular attraction between the particles of gas and that they are in a state of continuous motion.

(iii) The volume occupied by the gas molecules is negligible as compared to the volume of the gas.

Real gases differ from ideal ones due to presence of the intermolecular forces and also due to the finite molecular volumes. The Vander Waal's equation of state has been set up by incorporating the following two corrections into the equation of state, pv = RT

(i) Let the equation of state be presented in the form, $v = RT/P$. With increasing pressure, the volume diminishes and if $p \rightarrow \infty$, then $v \rightarrow O$. This aspect is in full agreement with the definition of an ideal gas, according to which, the molecules occupy an infinitely small volume. However, in real gases, the molecules occupy a finite volume and an allowance is also needed to be made for the volume of voids existing between molecules. As such, the free volume available for molecular motion shall be equal to $(v-b)$, where $b = v_{mol} + V_{void.}$ The quantity b, represents the smallest volume to which the gas can be compressed. For each real gas, the quantity b takes a definite numerical value.

(ii) Due to the presence of forces of molecular interaction in the real gases, there will be a small number of impacts with the walls of the container. This may be attributed to the fact that the molecules positioned at the wall are attracted by adjacent molecules inside the container. Consequently, compared to an ideal gas, the pressure exerted by a real gas will be smaller by a quantity ΔP. this pressure reduction is directly proportional to the number of molecules affected by molecular interaction or directly proportional to the square of the density of gas or inversely proportional to the square of its specific volume.

$$\Delta P = a\rho = a/v^2$$

Where the proportionality factor a has a definite numerical value for each gas.

When these two corrections are introduced, we obtain the Vander Waal's equation of state as follow:

$$(P + a/v^2)\ (V-b) = RT$$

IN the above equation,

(i) The coefficient b is intended to correct for the volume occupied by the gas molecules and is known as co-volume.

(ii) The term a/v^2 is a correction that accounts for the molecular forces of attraction. This term is called the forces of cohesion.

If the volume of one mole of gas is considered, then the Vander Waal's equation can be written as

$$(P + a \sqrt{v^2})\ (v$$

Where P is in N/m^2,

CHAPTER 6

PROPERTIES OF STEAM

6.1 INTRIDUCTION

Steam is a vapour of water and is invisible when it is when it is pure and dry. It does not obey the laws of perfect gases until it is perfectly dry.

6.2 FORMATION OF STEAM

Let us consider a unit mass of ice at 10°C and atmospheric pressure contained in piston – cylinder arrangement. Let us supply heat to the ice to convert it into steam.

Regime (A-B): The heat given to increases its temperure from - 10°C to 0°C. The volume of ice increases with the increase in temperature. Point B shows the saturated solid condition. At B, the ice starts melting.

Regime (B-C): The ice melts into water at constant pressure and temperature. The amount heat supplied per kg of substance is called latent heat of fusion. At C, the melting process ends. There is a sudden decrease in volume at 0°C as the ice starts melting.

Regime (C-D): The temperature of water increases on heating from 0°C to 100°C. The volume of water first decreases with the increases in temperature and reaches to its minimum at 4°C Fig and again starts increasing because of thermal expansion. Point D shows the saturated liquid condition.

Regime (D-E): The water start boiling at D. The liquid starts to get converted into vapour. The boiling ends at point E. Point E shows the saturated vapour condition at 100°C and I atm. The amount of heat supplied during the process is called latent of vapourization.

Regime (E-F): It shows the superheating of steam above saturated steam point. The volume of vapour increases rapidly and it behaves like a perfect gas. The difference between the superheating temperature and the saturation temperature at a given pressure is called degree of superheat. Points B, C, D and E are known as saturation states.

State B: Saturated solid state.

State C and D: Saturated liquid states. States C is for fusion and state D is for vaporization.

State E: Saturated vapour state.

At saturated states, the phase may get changed without change in pressure or temperature.

6.3 TYPE OF STEAM

The common types of steam are:

1. Wet Steam: When the steam contains moisture or particles of water in suspension, it is said to be wet steam.

2. Dry Saturated Steam: When the wet steam is further heated and it does not contain any suspended particle of water, it is known as dry saturated steam.

3. Superheated Steam: When the dry steam is further heated at a constant pressure, raising its temperature, it is said to be superheated steam. Since the pressure is constant therefore, the volume of superheated steam increases.

6.4 IMPORTANT TERMS FOR STEAM

Though, there are many terms applied to steam, yet the following are important from subject point of view:

1. Total heat or enthalpy of water: The quantity of heat absorbed by one kg of water at constant pressure from its freezing temperature to its saturation temperature is known as total heat or enthalpy water.

It is denoted by h_f and is approximately equal to sensible heat of water at low pressures.

Total heat of water = Sensible heat + work required to increase the pressure to that of the boiler.

At this stage, work required is negligible at low pressures, therefore, the total heat of water is also known as sensible heat of water.

2. Latent heat of steam: It is defined as the quantity of heat required to convert one kg **of** water at its boiling point into dry saturated steam at the same pressure. It is usually represented by h_{fg}. It is also called latent heat of vaporization and it decreases with the increases in pressure.

3. Total heat or enthalpy steam: It is the amount of heat absorbed by water from freezing point to saturation temperature plus the heat absorbed during evaporation.

∴ Enthalpy of steam = Sensible heat + Latent heat.

It is denoted by h_g and its value for the dry saturated steam may be read directly from the steam tables. The expressions for the enthalpy of wet steam, dry steam and superheated steam are as follow:

(i) Superheated steam: If the heat is added further to the dry steam, its temperature increases, while pressure remains constant. This increases temperature shows the superheat stage of the steam. Thus, total heat required for the steam to be superheated.

4. Dryness fraction: Dryness fraction is the ration of the mass of actual dry steam to the mass of same quantity of wet steam. It is generally denoted by x. mathematically,

5. Wetness fraction: Wetness fraction of steam is the ration of the mass of water vapour or moisture in suspension to the mass of same quantity of wet steam. It is generally denoted by y. mathematically,

6. Specific volume of steam: It is the volume occupied by the steam per unit mass at a given temperature and pressure and is expressed in m^3/kg. It is the reciprocal of density of steam. It may be noted that the value of specific volume decreases with the increases in pressure.

(i) Wet Steam: Let us consider 1 kg of wet steam of dryness fraction x. We know that this steam will have x kg of dry steam and (1-x) kg of water.

6.5 THE EFFECT OF INCREASES OR DECREASING PRESSURE

As the pressure is increased, the latent heat of fusion and vaporization starts decreasing. If we go an increasing the pressures further, a limiting pressure is reached called critical pressure (P_c). At this point, the latent heat of vaporization becomes zero and we cannot differentiate between liquid and vapour state above this point. The slope of any curve becomes zero at critical volume (vc).

The line joining saturated liquid points (D, D1, D2….) is called saturated liquid line and the line joining saturated vapour points (E, E1, E2….) is called saturated vapour line. Both the lines meet at critical point where latent heat of vaporization becomes zero.

6.6 THERMODYNAMIC PROPERTIES OF STEAM

The six basic thermodynamic properties: P, V, T, U, H, and S at various states are generally required in engineering problems for any fluid which is used as working substance. The values of these properties are determined theoretically o experimentally and are tabulated in from of tables and charts.

6.7 STEAM TABLES AND THEIR USES

The properties of dry saturated steam like its is temperature of formation (saturated temperature), sensible heat, latent heat of vaporization, enthalpy or total heat, specific volume, entropy etc. vary with pressure and can be found by experiments only. These properties have been carefully determined and made available in a tabular form known as steam tables.

6.9 INTERNAL LATENT HEAT

The difference between the latent heat external work done during evaporation is known as internal latent heat.

6.14 TEMPERATURE-ENTROPY (T-S) DIAGRAM AND ENTHALPY-ENTROPY (H-S) DIAGRAM

The solutions to problems dealing with steam vapours as working substance are easily and rapidly obtained by referring to charts/diagram which have been prepared by having the data from steam tables.

(a) Temperature-Entropy (T-s) Diagram

(i) The absolute temperature is plotted on the ordinate and entropy on the abscissa.

(ii) The liquid boundary line oridinate at a temperature of 273.16K. This is so because entropy of liquid at the triple is equal to zero.

(iii) The boundary curves (liquid line ABCDE) and the saturated vapour line (EFGHI) divides the diagram into three parts: To the left of AE is the liquid region, between the line AE and EL is the wet vapour region and to the right of line EI is the region of superheated steam.

(iv) The boundary curves meet at point E which is the critical point of water with pressure 221.27 bar and temperature 647.3k.

(v) The wet region has plots of constant dryness fraction and constant volume lines.

(b) Enthapy –Entropy (h-s) Diagram

It is the most convenient diagram to calculating the changes in enthalpy during different processes. The diagram is very useful for solving problems on nozzles and steam power plants.

Enthalpy is represented on Y-axis and entropy on X-axis for preparing the diagram. The point where saturated liquid lines and saturated vapour lines meet one another is called critical point. After this point, water directly gets changed into superheated steam.

$$dq = T.\,ds = dh$$

$$\therefore \qquad \left(\frac{dh}{ds}\right)_P = T$$

Or Slope of constant pressure lines will be equal to absolute temperature on h – s diagram. In wet region, the temperature of steam remains constant at a given pressure, therefore, the constant pressure line are straight lines in wet region. These lines bend upwards in superheated region.

The intercepts between saturated liquid and saturated vapour lines at different pressure are divided into equal parts and these points are joined to get constant fraction lines. This diagram also has constant temperature, constant fraction and constant specific volume lines.

6.16 MEASUREMENT OF QUALITY OF STEAM

To define the state of a pure substance, two independent properties are needed. There may be pressure and temperature, but the problem is due to inter-dependence of pressure and temperature in the dome region. If the pressure is known, the temperature can be found out because for each saturation pressure, there is a fixed saturation temperature and vice versa. Thus, we need one more term other than the pressure or temperature, which may be specific volume, enthalpy or quantity of mixture (liquid + vapour). Since, it is relatively difficult to measure the specific volume of mixture, devices such as calorimeters are used for determining the quality of the mixture.

1. Measurement of quality using separating calorimeter

Working: The separating calorimeter is shown in fig.

The steam collected from steam main is passed down the central passage, where sudden reversal of direction of motion takes place when it strikes the baffle plates. It causes the water to separate out from mixture due to greater inertial. This water gets collected in the inner chamber which is connected to gauge glass with a graduated scale showing the quantity of water separated. The remaining dry steam moves to the annular space between inner and outer chambers. A gauge is fitted to outer surface which is calibrated to give the discharge of dry saturated steam in a fixed interval of time say 10 Minutes. The gauge also has a calibrated scale to show the gauge pressure.

2. Measurement of quality using throttling calorimeter

Working: The sampled steam is passed through a throttle valve and the throttle steam flows into the inner chamber. The pressure after throttling atmospheric of a few mm of hg above the atmospheric pressure a recorded by manometer. Corresponding to this pressure saturated temperature can be obtained from steam tables. The temperature recorded by the thermometer should be more than this saturation temperature. This difference in temperature is called degree of superheat. Generally, about 5°C of superheat is kept to ensure that steam is superheated after throttling. The steam then flowing out of the inner chamber at the top, turns downwards into the annular space between inner and outer chamber and then exhausted to atmosphere.

CHAPTER 7

STEAM GENERATORS

7.1 INTRODUTION

A steam generator or boiler is usually a closed vassel made of steel whose function is to transfer the heat produced by the combustion of fuel (solid, liquid or gaseous) to water and ultimately to generate steam.

According to American Society of Mechanical Engineers (A.S.M.E.), a steam generating unit is defined as:

“A combination of apparatus for producing furnishing or recovering heat together with the apparatus for transferring the heat to made available to the fluid being heated and vapourised”.

The steam produced may be used:

1. In an external combustion engine i.e. steam engines and turbines.

2. At low pressures for industrial process work in cotton, mills, sugar factories etc.

3. For producing hot water which can be used for heating installations at much lower pressures.

4. For heating the building in cold weather and for producing hot water for hot water supply.

7.2 CLASSIFICATION OF BOILERS

There are numerous ways in which the boilers may be classified which are as follow:

1. According to the contents in the tubes: The steam boilers, according to the contents in the tubes, may be classified as:

(a) Fire tube boilers, (b) Water tube boilers.

Fire tube boilers, the flames and hot gases produced by the combustion of fuel pass through the tubes which are surrounding water. e.g. Cochran boiler, Lancashire boiler, Cornish boiler, Cornish boiler, Scotch marine boiler.

Water tube boilers, the water is contained inside the tubes (called water tubes) which are surrounded by flames and hot gases from outside e.g. Babcock and Wilcox, boiler, Stirling boiler, yarrow boiler, La-Mont boiler, Benson boiler, Loeffler boiler.

2. According to the position of the furnace: The steam boilers, according to the position of the furnace, are classified as:

(a) Externally fired boiler, (b) Internally fired boilers.

If the space where the combustion of the fuel takes place is provided outside the boiler shell, the boiler is called externally fired boiler. e.g. Babcock and Wilcox boiler, Stirling boiler etc.

The boiler in which the furnace is provided inside the boiler shell are said to be internally fired boiler. e.g. Lancashire boiler, Cochran boiler, and Locomotive boiler.

3. According to the axis of shell: The steam boilers, according to the axis of the shell, may be classified as:

(a) Vertical boiler (b) Horizontal boiler (c) Inclined boilers.

If the axis of the boiler is horizontal, the boiler is called as horizontal boiler. e.g. Lancashire boiler, Locomotive boiler etc.

If the axis of the boiler is Vertical, it is called boiler. e.g. Simple Vertical boiler and Cochran boiler.

4. According to the Number of Tubes: The steam boiler, according to the number of tubes, may be classified as:

(a) Single tube boilers, (b) Multiubular boilers.

In single tube boiler, there are is only fire tube or water tube. E.g. Vertical boiler and carnish boiler.

In multiubular

7.3 COMPARISON BETWEEN WATER TUBE AND FIRE TUBE BOILERS

The detailed comparison between the water tube boiler and fire tube boiler is given as below:

S.No.	Water Tube Boiler	Fire Tube Boiler
1.	Water flows inside the turbine and hot flue gases outside the tube.	Hot flue gases flow inside the tube and the water outsides the tubes.
2.	These boilers are generally extra really fired.	These boilers are generally internally fired.

3.	The boiler pressure is limited to up to 100 bar.	The boiler pressure limited to 20 bar.
4.	A higher rate of steam production.	The fire-tube boiler has a lower rate of steam production.
5.	Suitable for larger power plants.	Not suitable for larger power plants.
6.	The risk of the explosion is higher due to high boiler pressure.	Involves lesser risk of explosion due to low pressure.
7.	Simple in construction.	This boiler is difficult to construct.

7.4 ESSENTIALS OF A GOOD BOILER

Following are the essentials of a good steam boiler:

1. It should be economical to install and should require little attention during operation.
2. It should be light in weight.
3. It should occupy small space.
4. It should rapidly meet the fluctuation of load.
5. It should be capable of quick starting.
6. It should allow easy maintenance.
7. The joints in the boiler should be few and accessible for inspection.
8. It should comply with safety regulations as laid down in the Boiler Act.

7.5 SELECTION OF A STEAM BOILER

The following factors must be taken into consideration while deciding the type and size of the boiler required for a specific purpose.

(i) The power required and working pressure.

(ii) The rate at which steam is to be generated.

(iii)Initial cost and facilities available for erection.

(iv) Availability of the floor area.

(v) Operating and maintenance cost.

(vi) The type of fuel to be used.

(vii) The probable load factor.

7.6 LANCASHIRE BOILER

CHAPTER 8

AIR STANDARD CYCLES

8.1 CYCLE

A cycle is a series of thermodynamic operations which occur in a certain order and initial conditions are restored at the end. The cycle may be imaginary or actual. An imaginary cycle may also be called as an ideal cycle.

8.2 AIR STANDARD EFFICIENCY

To compare the effects of different cycles, it is important that the effect of calorific value of fuel be eliminated and this can be approached by considering air as the working substance. A thermodynamic cycle using air as the working substance is known as air standard cycle and the efficiency of this cycle is known as air standard efficiency.

The actual efficiency of a cycle is always less than the air-standard efficiency. Hence, a new term relative efficiency is introduced which is defined as :

8.3 REVERSIBLE AND IRREVESIBLE PROCESSES

A reversible process (also known as quasi-static process) is one which can be stopped at any stage and can be operated in the reverse direction. In order words, it may also be defined as the process which can retrace the same path in the reverse direction, so as to bring back the original conditions.

Some examples of nearly reversible processes are:

(i) Frictionless adiabatic expansion or compression of fluid.

(ii) Isothermal expansion or compression.

(iii) Polytropic expansion or compression of fluid.

An irreversible process is that process in which process cannot be repeated exactly in the reverse direction. e.g. Throttling, Heat transfer, Free-expansio,

8.4 REVERSIBLE CYCLE

A cycle which consists of the reversible is known as reversible cycle. In such a cycle shown in fig (a) heat is absorbed from a hot body and rejected to the cold body. Mechanical work is produced in this cycle and is represented by the area of the diagram.

When the cycle is reversed i.e. heat is extracted from the cold body and rejected to the hot body, there is a need of some external work done. This process is shown in fig.

8.4.1 Conditions of Reversibility of a cycle

Following conditions must be satisfied for thermal reversibility of a cycle:

(i) The temperature of working substance and the hot body should be same when the heat is absorbed.

(ii) The temperature of working substance and the cold body should be same when the heat is rejected.

(iii) The heat loss by conduction, convection and radiation should be negligible.

8.5 HEAT ENGINE AND REVERSED ENGINE

A heat engine is used to produce the maximum work from a given positive heat transfer. The thermal efficiency is used to find the performance of a heat engine.

Thermal efficiency,

Where Q_1 = Heat transfer to engine,

W = Net work transfer from the engine.

A reversed heat engine acting as a refrigerator is used to extract heat from clod reservoir and deliver to hot reservoir with the help of external work done. The term coefficient of performance (C.O.P) is used to find the performance of a reversed heat engine or refrigerator.

8.6 CARNOT CYCLE

The cycle was first devised by a French scientist, cannot in 1824 which operates on reversible cycle. In a cannot cycle, working substance is subjected to two isothermal and two adiabatic or isentropic processes.

The following assumptions are made in the carnot cycle.

1. The wall of the cylinder and piston are perfect non-conductor of heat.
2. In the cylinder, piston motion should be frictionless.
3. Working medium and is a perfect gas having constant specific heat.
4. Compression and expansion processes are reversible.

Now, let us consider the four stages of the carnot cycle.

1. First Stage (Isothermal Expansion, 1-2): The source (hot body) at a high temperature is applied at the bottom of cylinder. The air expands at constant temperature T_1 from V_1 to V_2. It means that temperature at point 1, T_1 is equal to temperature at point 2, T_2. It may be noted that heat supplied by hot body is fully absorbed by the air for doing work.

2. Second Stage (Adiabatic or Isentropic Expansion, 2-3): AS the cylinder is assumed to be a perfect insulator of heat, so no heat flow taking place. The air expends adiabatically and temperature falls from T_2 to T_3.

3. Third Stage (Isothermal Compression, 3-4): The cold body is brought in contact with cylinder. The air is compressed at a constant temperature T_3 from V^3 to V_4. During this process, temperature T_3 is equal to temperature T_4 and heat is rejected to the cold body and is equal to the work done on the air.

4. Fourth Stage (Adiabatic or Isentropic Compression,4-1): Again the cylinder head becomes perfect insulator of heat so that no heat flow occurs. The compression process follows reversible adiabatic process during which temperature is raised from T_2 to T_1.

8.7 OTTO CYCLE OR CONSTANT VOLUME CYCLE

The first successful engine working on Otto cycle was build by A. Otto. These days, many petrol, gas and oil engines work on this cycle. It is also known as constant volume cycle, as heat is received and rejected at a constant volume. This cycle is basically used as a standard of comparison for internal combustion engines.

The Otto cycle consists of the constant volume and two reversible adiabatic or isentropic processes as shown in fig. Air is used as a working substance for different operations in this cycle.

Let P_t, V_1 and T_1 are the pressure, volume and temperature of air at point I. let the mass of air in the engine is m kg.

1. First Stage (Reversible Adiabatic or Isentropic Expansion, 1-2): In this process, the pressure. Volume and temperature changes from P_1, V_1 and T_1 to P_2, V_2 and T_2 due to isentropic expansion. No heat is absorbed or rejected by air during this process.

2. Second Stage (Constant Volume Cooling, 2-3): The heat is rejected at constant volume from temperature T_1 to T_2 during this process.

3. Third Stage (Reversible Adiabatic or Isentropic Compression, 3-4): The compression of air takes place reversible and adiabatically from temperature T_3 and T_4 Volume of air decreases from V_3 and V_4. No heat is absorbed or rejected by air.

4. Fourth Stage (Constant Volume Heating, 4-1): The air is heated at constant volume from temperature T_4 to T_1.

CHAPTER 9

AIR COMPRESSORS

9.1 INTRODUCTION

An air compressor is a device which compresses the air and raises its pressure. The air compressor sucks from the atmosphere, compresses it and delivers the compressed air to a storage vessel. From the storage vessel, compressed air can be distributed through pipelines to the required place. The external work done for compressing the air is done by same external device or prime mover. The schematic diagram of a compressor prime mover unit is sown in fig.

9.2 USES OF COMPRESSED AIR

Compressed air is used in the following areas:

(i) It is widely used for powering small engines e.g in starting and supercharging of internal combustion engines, in gas turbine plants, in jet engines and air motors, in operating brakes on buses, trucks and trains etc.

(ii) It is used for producing blast of air in blast furnaces.

(iii) It is used in the operation of lifts, pumps, rams etc.

(iv) It is used in operating drills and in hammering operation.

(v) It is also used for spraying of insecticides in the agriculture sector.

9.3 CLASSIFICATION OF COMPRESSORS

Air compressors can be classified by many different ways which are as follow:

1. According to working

(a) Reciprocating compressors, (b) Rotary compressors,

2. According to number of stages

(a) Single stage compressors, (b) Multi-stage compressors,

3. According to action

(a) Single acting compressors, (b) Double acting compressors,

4. According to compressed air capacity

(a) Low capacity compressors, (b) Medium capacity compressors,

(c) High capacity compressors,

5. According to nature of installation

(a) Fixed, (b) Semi-fixed,

(c) Portable.

6. According to cooling

(a) Water cooled compressors, (b) Air cooled compressors,

9.4 TECHNICAL TERMS

The following technical terms should be clearly understood before taking up actual study of compressors:

(i) Inlet Pressure: It is the absolute pressure of the air at inlet of a compressor.

(ii) Discharge Pressure: It is an absolute pressure of air at the outlet of a compressor.

(iii) Pressure Ratio: It is the ration of discharge pressure to the inlet pressure. it is always greater than one as the discharge pressure is always greater than inlet pressure.

(iv) Capacity: It is the volume of air delivered by compressor and is expressed in m^3/s or m^3/min.

(v) Swept Volume: It is the volume of air sucked by compressor during suction stroke. swept volume of a single acting reciprocating compressor is given by

$$V_s = \frac{\pi}{4} D^2 L$$

D = Diameter of cylinder bore,

L= Stroke length of piston.

(vi) Free Air Delivery: It is the volume of air delivered by a compressor when reduced to normal temperature and pressure conditions. The capacity of compressor is generally given in terms of free air delivery.

9.5 SINGLE STAGE RECIPROCATING AIR COMPRESSOR

A single stage reciprocating air compressor consists of a cylinder, piston inlet and discharge valves as shown in fig. during operation, flywheel gives the turning moment to main shaft which is connected to piston through crankshaft and connecting rod.

During suction stroke, the piston moves downwards and the pressure inside the cylinder fall below the atmospheric pressure. Due to this difference, the inlet valve opens and air is sucked into the cylinder. In case of mechanically operated valves, these are operated by cams. During compression stroke, the piston moves upwards and the pressure inside the cylinder increases till it reaches the discharge pressure. When pressure becomes high in cylinder, the discharge valve gets opened and air is delivered to the storage tank. At the completion of delivery stoke, a small quantity of air is left in the clearance space. When the cycle start again, this residual air expands till pressure falls below the atmospheric pressure.

9.7 MULTI STAGE COMPRESSION

In case of a single stage reciprocating air compressor, suction, compression and delivery of air take place in a single stage. But sometimes, the air is required at a higher pressure. For this, we can either employ a large pressure ration in a single cylinder or compress the air in two or more cylinders in series. Now, if we employ single stage compression for producing higher pressure air (say 8 to 10 bar), certain disadvantage occur which are as follow:

(i) Cylinder size will be large.

(ii) Temperature at the end of compression may be so high that it can heat up the cylinder head or burn the lubricating oil.

(iii) Due to increase in pressure, time available for delivery of air also reduces.

9.7.1 Advantages of Multistage Compression

1. The power required to drive a multistage compressor with intercooler is less than that would be required by a single stage compressor for the some delivery pressure.

2. Multistage compressor has better mechanical balance and hence and hence, a smaller sized flywheel is required.

3. It reduces the leakage loss considerably.

4. It reduces the cost of compressor.