MODULE 1
FUNDAMENTAL CONCEPTS AND DEFINITIONS

OBJECTIVE:
Students will be familiar with
- **Thermodynamic concepts.**
- **Zeroth law of thermodynamics**

STRUCTURE:
1.1.1 Introduction
1.1.2 Basic concepts and definitions
1.1.3 Zeroth law of thermodynamics
**1.1.4 Measurement of Temperature.**
1.1.5 Comparison of Temperature Scales:

1.1.1 Introduction:

- ➢ Thermodynamics is derived from two greek words Therme which means HEAT & Dynamics with mean STRENGTH/POWER.
- ➢ Thermodynamics is the science of energy transfer and its effect on the physical properties of a substance.
- ➢ Its application is in
  - Steam & Nucelar power plant
  - IC Engines
  - Gas turbines
  - Air Conditioning
  - Refrigeration
  - Jet Propulsion Etc.

1.1.2 Basic concepts and definitions:

- ➢ **System:** It is defined as a quantity of matter or a Region in space chosen for study.
- ➢ **Surroundings/Environment:** The mass or region outside the system is called Surroundings.
- ➢ **System Boundary:** The real or imaginary surface that separates the system from its surroundings is called the system boundary or just boundary.
- ➢ **Universe:** Combines System & Surroundings forms Universe.
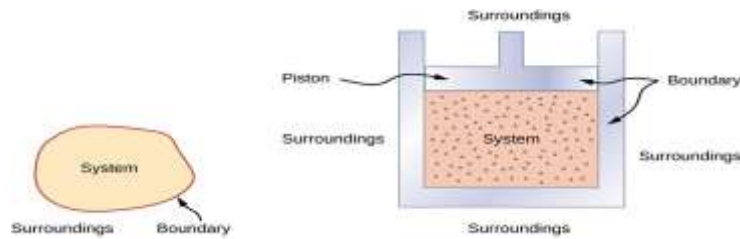
❖ **Types of Systems:**

a) **Closed system:** System of fixed content or matter (mass) in which only energy transfer takes place is called Closed system. Thus in a closed system, mass doesn't cross the system boundary even though energy may cross the system boundary. For Example of a closed system – a pressure cooker with closed Lid.
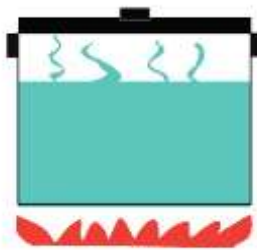

Fig 1.1: Closed system

b) **Open System:** System in which both mass and energy interaction takes place across the system boundary. **For example:** boiling water without a lid. Here Heat escape into the air. At the same time steam (which is matter) also escapes into the air.
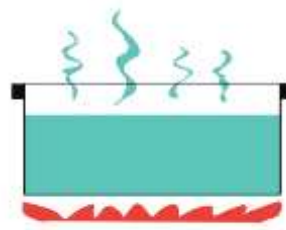

Fig 1.2: Open system

c) **Isolated System:** In an isolated system neither mass nor energy crosses the system boundary. **For example:** A thermoflask is an isolated system.

➢ **Control Volume:** It is defined as volume in space through which matter, momentum and energy may flow. The control volume may be stationary or may be moving at a constant velocity. If control volume changes both in size and in position, the control volume is equivalent to an open system. If no mass transfer occurs then it is equivalent to closed system.

➢ **Control Surface:** Control volume is bounded by a surface called control surface.
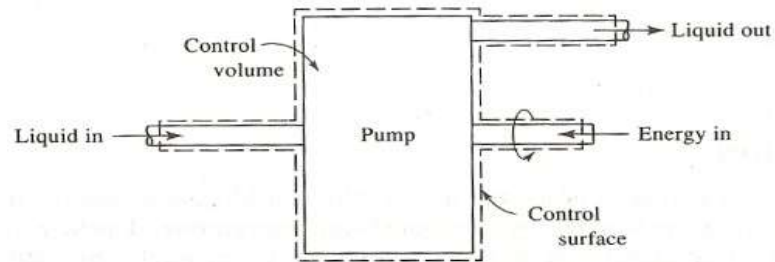
Example for Control Volume and Control Surface

➢ **Macroscopic and Microscopic Approach/Point of View:**

SL.No	Microscopic Approach	Macroscopic approach
Table 1: Differentiation of Microscopic and Macroscopic Approach		
1	This approach considers that the system is made up of a very large number of discrete particles known as molecules. These molecules have different velocities and energies.	In this approach the behaviour of individual molecules is not considered but studies the properties of particular mass of the substance.
2	The behaviour of system is found by using statistical method as the number of molecules is very large	The analysis of macroscopic system requires simple mathematical formulae
3	The properties like velocity, momentum, impulse, Kinetic energy etc, which describes the molecules cannot be easily measured by instruments	The properties like temperature and pressure which are required to describe the system can be easily measured by instruments.
4	Large number of variables is needed to describe such a system. So approach is complicated	Only few properties are needed to describe such system

➢ **Phase:** A Quantity of mater which is homogeneous in chemical composition and in physical structure is called a Phase.

Example: Solid phase: Ice

Liquid Phase: Water

Gaseous Phase: Water vapour /Steam

➢ **Homogeneous System:** A system is called as Homogeneous system if it consists of a single phase. Example water inside a container.

➢ **Heterogeneous System:** A system consisting of more than one phase is called Heterogeneous System. Example: Ice in liquid water.

➢ **Property:** Any characteristic of a system is called Property. It is defined as any quantity that depends on the state of the system and is independent of the path by which the system has reached the given state. Example: Pressure, Volume, Temperature, Mass, Modulus of Elasticity, Electric Resistivity, Thermal Expansion Coefficient Etc.

❖ Classification of Property:

a) **Intensive Property:** Properties that are independent of the mass of the system Example: Temperature, Pressure, Density **(Density of water is constant i.e 1000kg/m3 and the value does not depends on mass of water).**

b) **Extensive Property:** Properties that are dependent of the mass or extent of the system. Example: Mass, Volume, Entropy, Enthalpy, Energy Etc.

c) **Specific Property:** Extensive Property Per unit mass are called Specific Property. Example: Specific Volume (v), Specific Enthalpy (h), Specific Energy (e) Etc.

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➢ **State of a system**: It is the condition of existence of a system at a particular instant. Example: Liquid can exist in Solid liquid & Gaseous phase at each phase the property values will be different which denotes the state of the system.

➢ **Concept of Continuum:** Since thermodynamics doesn't deal with the behaviour of individual molecule we treat the substance as continuous ignoring the action of individual molecule. This Concept is known as continuum.

**"The continuum hypothesis states that large systems made up of many discrete molecules or atoms may be treated as though they are made up of continuous material"**

Discrete Molecues

Single Molecule or Continuous material
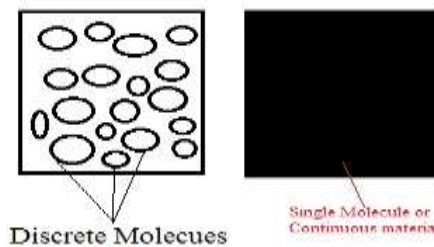
➢ **Thermodynamic Process:** It is defined as the path of the thermodynamic states that a system passes through as it goes from an initial state to a final state.
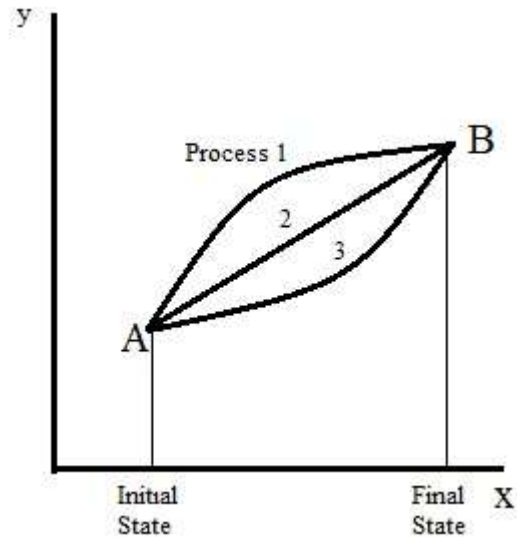
> ➤ **Path of a process**: The series of states thrpugh which a system passes during a process is called the Path.
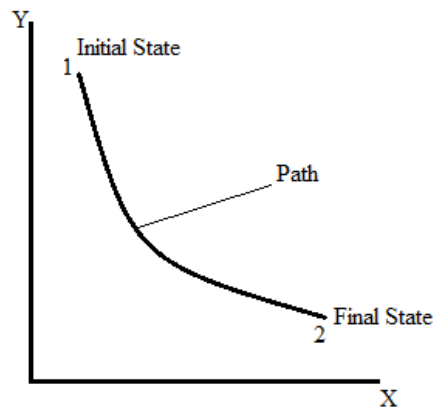
> ➤ **Equilibrium Process:** If the process goes on so slowly that the state of equilibrium exists at every moment, then such a process is referred to as an equilibrium process otherwise it is referred to as a Non-equilibrium process.

> ➤ **Quasi-Static or Quasi-Equilibrium Process:** "When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times is called a Quasi-static Process.

Quasi static process: Example

Let us consider the assembly of cylinder and piston as shown in figure. Cylinder is contained with gas and system is in equilibrium condition initially. Let us see the state of the system initially is at state 1 and indicated by its thermodynamic properties P1, V1 and T1. At this state pressure will be high and specific volume will be less at a temperature
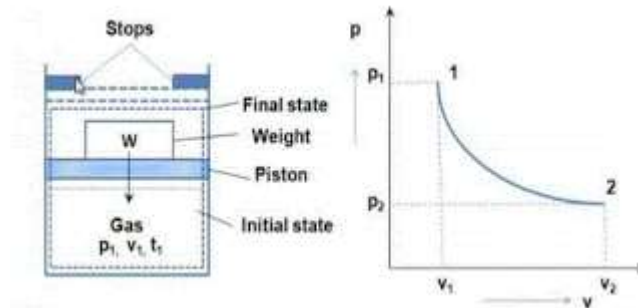

Weight placed over the piston is just balancing the force which is exerted in upward direction by gas. If we remove the weight from the piston, system will have unbalanced force and piston will move in upward direction due to force acting over the piston in upward direction by the gas.

Piston will move in upward direction and will be stopped once it will strike the stops. This condition of the system is expressed as final state and indicated by state 2 and will have its thermodynamic properties P2, V2 and T2. At this state pressure will be less and specific volume will be high.

Initial and final state of the system displayed here with the help of thermodynamic properties as state 1 and state 2 respectively, but intermediate states could not be displayed here by thermodynamic properties as intermediate states by which system has arrived at state 2 were not in equilibrium condition.

Quasi-static processes
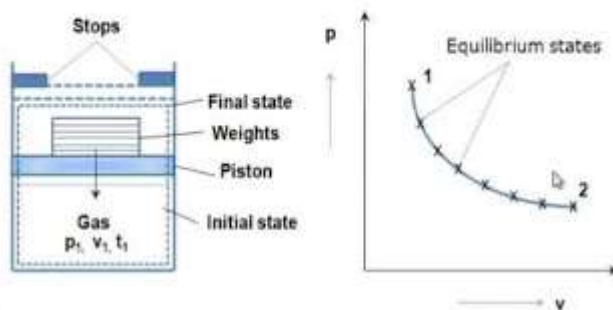
Let us consider the above single weight, placed over the piston, replaced by few infinitesimally small weights and these infinitesimally small weights are placed over each other and also resultant weight of all infinitesimally small weights is equivalent to the single weight placed earlier over the piston.

When we remove the first infinitesimally small weight from the piston, piston will move very slowly as well as with infinitesimally small amount and will secure its next equilibrium state. Due to removal of infinitesimally small weights, one by one and also quite slowly, system will process from one state to another state with succession of equilibrium states.

Hence we can say here that system will arrive to final state from initial state with various equilibrium intermediate states and these intermediate states are displayed in above figure.

Such a process, where system process in such a manner as studied above, will be termed as quasi static process or quasi equilibrium process in the field of thermal engineering.

➢ **Thermodynamic Cycle:** It is the one in which a system in a given state goes through a number of different process & finally returns to its initial state .Example: Steam Power Plant constitutes Steam cycle.
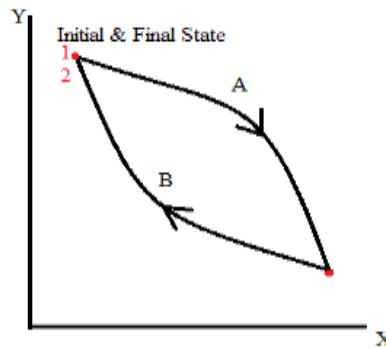
From figure the system follows process A and Process B and comes back to initial state 1. If a system undergoes cyclic process then its initial and final state will be same (1 & 2).

➢ **Reversible Process:** It is defined as the process that occurs in a reverse direction such that the initial state & all energies transferred or transformed during the process can be completely restored in both system and surrounding. In this process there will be no net change in the system or in the surroundings. Example: Reversible adiabatic process.
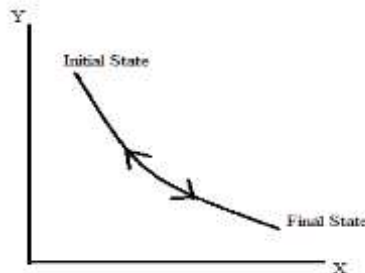
➢ **Irreversible Process:** It is defined as the process that is not reversible. Thus during such process the system & the surroundings are no restored to their initial state, if it is restored also their respective

initial states with a net change in the system & in the environment. Example: Flow through pipes involving friction.

➢ **Thermodynamic Equilibrium:** When all the conditions of mechanical, chemical, thermal, electrical equilibrium are satisfied, the system is said to be in Thermodynamic Equilibrium.
   1. **Mechanical Equilibrium:** System is said to be in Mechanical equilibrium if there is no unbalanced force within the system or at its boundaries.
   2. **Chemical Equilibrium:** System is said to be in chemical equilibrium when there is no chemical reaction or a process such as diffusion within the system or at its boundaries.
   3. **Thermal Equilibrium:** System is said to be in thermal equilibrium when there is no temperature gradient within the system or between the system and its surroundings.
   4. **Electrical Equilibrium:** System is said to be in electrical equilibrium when there is no electrical potential gradient within a system or between the system and its surroundings.

➢ **Equality of Temperature:** When two systems at different temperatures are perfectly insulated from the surroundings and brought into contact their will be changes in their physical properties. After some period of time both physical properties and temperature remains constant. This concept is called **Equality of Temperature.**

1.1.3 Zeroth Law of Thermodynamics: "If two bodies are in thermal equilibrium with a third body separately, then they are also in thermal equilibrium with each other.
   Or
   "If body A is in thermal equilibrium with body B and also separately with body C, then B and C will be in thermal equilibrium with each other.
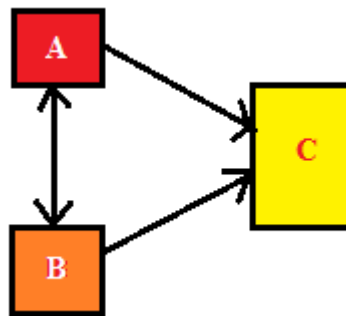
➢ **Temperature:** It is the measure of the average heat or thermal energy of the particles in a substance. It does not depend on the size or type of object **(OR)** it is a measure of degree of hotness and coldness of the body.

➢ **Thermometric property:** The characteristics or physical properties oa a reference body which changes with temperature is called thermometric property.
   The reference body which is used in the determination of temperature is called **Thermometer.**

Type of thermometer	Thermometric Property	Symbol
Constant Volume Gas Thermometer	Pressure	P
Constant Pressure Gas Thermometer	Volume	V
Electrical Resistance Thermometer	Resistance	R
Thermocouple	Thermal emf	ε
Liquid in Glass Thermometer	Length	L

1.1.4 Measurement of temperature:

1) **Two standard fixed points method:**
   To establish a temperature scale an easily reproducible state of an arbitrarily chosen standard system is considered which is called fixed points i.e ICE POINT and STEAM POINT.
   ICE POINT: The lower fixed point or ice point is the temperature at which pure ice melts at standard pressure.
   STEAM POINT: The upper fixed point or steam point is the temperature at which pure water boils at standard pressure.
   These points are considered as fixed points. In this method the thermometer is first placed in contact with the system whose temperature $\theta(X)$ is to be measured, then it is placed in contact with arbitrarily chosen standard system at ice point where temperature is say $\theta(X_1)$. The variation of temperature can be assumed to be a linear function of 'X' which is a thermometric property.
   Hence for the first system
   $$\frac{\theta(X_1)}{\theta(X)} = \frac{X_1}{X}$$
   Then the thermometer at temperature $\theta(X)$ is placed in contact with another chosen standard system at steam point where temperature is $\theta(X_2)$.
   Hence for the second system
   $$\frac{\theta(X_2)}{\theta(X)} = \frac{X_2}{X}$$
   By dividing the equations we get

   $$\frac{\theta(X_1) - \theta(X_2)}{\theta(X)} = \frac{X_1 - X_2}{X}$$

   $$\theta(X) = \left[\frac{\theta(X_1) - \theta(X_2)}{X_1 - X_2}\right].X$$

2) **Single standard fixed point method:**
   Kelvin pointed out that a single fixed point such as triple point of water where ice, liquid water and water vapour co-exist in equilibrium. The temperature at which this state exists is arbitrarily assigned the value of 273.16K.
   If θ_t = Triple point of water

X_t = Thermometric propert when the body is placed in contact with water at its triple point. Then we can write,

$$\theta_t = a.X_t$$

$$a = \frac{\theta_t}{X_t} = \frac{273.16}{X_t}.X$$

and if $\theta = a.X = \frac{273.16}{X_t}.X$

$$\theta = \frac{273.16}{X_t}.X$$

Different Types of Thermometer:

1) **Liquid in glass thermometer:** A small quantity of liquid enclosed in a glass capillary is called liquid in glass thermometer. In this the thermometer, the expansion of the liquid which is the length of liquid column is used as the thermometric property Example: Mercury in glass thermometer.

$$\boldsymbol{\theta(L) or\ T(L) = 273.16\left[\frac{L}{L_{tp}}\right]}$$

2) **Constant Volume Gas Thermometer:** It consists of a capillary tube, a gas bulb and a U-tube manometer with flexible tubing. The flexible bend is used to raise or lower the limb which is kept opened to the atmosphere. This helps in adjusting the meniscus of mercury upto the fixed point 'A' and hence maintains constant volume in the gas bulb. The capillary tube connects the bulb to one limb of the manometer whereas; the other limb is kept open to atmosphere. The pressure in the bulb is used as a thermometric property and is given by

$$P = P_o + \rho_M.g.h.$$

Where, P_o = Atmospheric pressure, ρ_M = Density of Mercury

When the bulb is brought in contact with the system whose temperature is to be measured, Heat transfer from the system into the bulb takes place and the bulb in course time comes in thermal equilibrium with the system. Due to heat addition the gas in the bulb expands and pushes the mercury level downwards. The flexible limb of the manometer is then adjusted so that the mercury again touches the fixed mark 'A' (For keeping volume of gas constant). The difference in the mercury level 'h' is recorded and the pressure 'P' of the gas in the bulb is estimated by using the formulae. Thus temperature increase is proportional to the pressure increase when volume is kept constant in constant volume gas thermometer.

In **constant pressure gas thermometer** the mercury levels have to be adjusted to keep 'h' constant and the volume of gas 'V', which would vary with the temperature of the system becomes the thermometric property. Thus temperature increase is proportional to the volume increase when pressure is kept constant.

International Temperature scale:

Fixed Points	Standard system at 1atm Pressure	Temperature	
		°C	K
Oxygen point	Normal boiling point of oxygen	-182.97	90.19
Ice point	Melting point of ice	0	273.16
Steam point	Normal boiling point of water	100	373.16
Sulphur point	Normal boiling point of sulphur	444.60	717.76
Silver point	Melting point of silver	960.80	1233.96
Gold point	Melting point of gold	1063	1336.16

Different types of scales:

Temperature Scale	Ice point	Steam Point	Triple Point
Kelvin Scale	273.15K	373.15K	273.16K
Rankine Scale	491.67R	671.67R	491.69R
Fahrenheit Scale	32°F	212°F	32.02°F
Centigrade Scale	0°C	100°C	0.01°C

1.1.5 Comparison of Temperature Scales:

Let the Temperature 'T' be linear function of thermometric property 'L' of the mercury column.
Considering the Celsius scale

T = a.L + b ……………(1)

Where a and b are constants

Applying the above equation for steam point and ice point respectively, we have

$100 = a. L_S + b$

$0 = a. L_I + b$

Solving the above equation for a and b we get

$a = 100 / (L_S - L_I)$

$b = -100 / (L_S - L_I)$

Substituting a and b in equation (1) we get

$$T(°C) = \left[\frac{L - L_I}{L_S - L_I}\right] \times 100$$

Similarly for Fahrenheit , Rankine and Klevin scale we get

$$T(°F) = \left[\frac{L - L_I}{L_S - L_I}\right] \times 180 + 32$$

$$T(R) = \left[\frac{L - L_I}{L_S - L_I}\right] \times 180 + 491.67$$

$$T(K) = \left[\frac{L - L_I}{L_S - L_I}\right] \times 100 + 273.15$$

Relation between scales:

$$T(°C) = \frac{5}{9}[T(°F) - 32]$$

$$T(°C) = \frac{5}{9}[T(R) - 491.67]$$

$$T(°C) = \frac{5}{9}[T(K) - 273.15]$$

$$T(R) = T(°F) + 459.67 = 1.8 \times T(K)$$

IMPORTANT THEORY QUESTIONS:

1) Distinguish between i)Microscopic and Macroscopic approaches ii) Intensive and Extensive property iii) Point and Path function iv) Quasistatic and Actual process v) Open and close system vi) Adiabatic wall and diathermic wall.
2) Define thermodynamic equilibrium. Explain different conditions that a system should satisfy to attain thermodynamic equilibrium.
3) Explain zeroth law of thermodynamics. How this law forms the basis of temperature measurement.
4) Name a few measurements (or) quantities that can be conveniently used as thermometric properties in order to quantify the temperature.

PROBLEMS:

1) The reading t_A and t_B of two Celsius thermometers A & B agree at the ice point and steam point and are related by the equation $t_A = L + M.t_B + N.t_B^2$. Between these two points L,M,N are constants. When both are immersed in an oil bath, thermometer 'A' indicates 55°C and thermometer 'B' indicates 50°C. Determine the values of L,M,N and also find the reading on 'A' if 'B' reads 25°C.

Solution: As the two thermometers A and B agree at the ice point and steam point we have

at Ice point : $t_A = 0°C$, $t_B = 0°C$

$t_A = L + M.t_B + N.t_B^2$

$0 = L + 0 + 0$

L = 0

at Steam point: $t_A = 100°C$, $t_B = 100°C$

$$t_A = L + M.t_B + N.t_B^2$$
$$100 = L + M.100 + N.100^2$$
$$\mathbf{M = 1 - 100.N}$$

when 'A' indicates 55°C , 'B' indicates 50°C hence

$$t_A = L + M.t_B + N.t_B^2$$
$$55 = 50.M + 2500.N$$
$$11 = 10.M + 500.N$$

Substituting for 'M' in the above equation we get

$$\mathbf{N = \frac{-1}{500}}$$

From equation $M = 1 - 100.N$

$$\mathbf{M = 6/5}$$

When thermometer 'B' reads 25°C , thermometer 'A' reads

$$t_A = L + M.t_B + N.t_B^2$$
$$t_A = 28.75°C$$

***Thus when 'B' reads °C , 'A' reads* 28.75°C**

2) The e.m.f in a thermocouple with the test junction at $t°C$ on gas thermometer scale and reference junction at ice point is given by $\varepsilon = 0.20.t - 5\times10^{-4}.t^2$ mV. The millivoltmeter is calibrated at ice and steam points. What will this thermometer read in a place where the gas thermometer reads **50°C.**

Solution: At ice point, when t = 0°C , $\varepsilon_I = 0$ mV

At steam point , when t = 100°C , $\varepsilon_s = [0.20\times100] - [5\times 10^{-4}\times(100)^2]$

$$\varepsilon_s = 15mV$$

At t = 50°C , $\varepsilon = (0.20\times50) - [5\times 10^{-4}\times(100)^2] = 8.75mV$

For linear scale we have

$$t(°C) = \left[\frac{\varepsilon - \varepsilon_I}{\varepsilon_S - \varepsilon_I}\right] \times 100$$

When $\varepsilon = 8.75$ m.V $t(°C) = 58.33°C$

***Thus when gas thermometer reads* 50°C*, thermocouple reads* 58.33°C**

3) In 1709, Sir Issac Newton proposed a new temperature scale. On this scale, the temperature was a linear function on Celsius scale. The reading on this at ice point (0˚C) and normal human body temperature (37˚C) were O˚N and l2˚N, respectively. Obtain the relation between the Newton scale and the Celsius scale.

List of Formulae:

1. $T(°C) = \frac{5}{9}[T(°F) - 32]$

2. $T(°C) = \frac{5}{9}[T(R) - 491.67]$

3. $T(°C) = \frac{5}{9}[T(K) - 273.15]$

4. $T(R) = T(°F) + 459.67 = 1.8 \times T(K)$

5. $T(°C) = \left[\frac{L - L_I}{L_S - L_I}\right] \times 100$

6. $T(°F) = \left[\frac{L - L_I}{L_S - L_I}\right] \times 180 + 32$

7. $T(R) = \left[\frac{L - L_I}{L_S - L_I}\right] \times 180 + 491.67$

8. $T(K) = \left[\frac{L - L_I}{L_S - L_I}\right] \times 100 + 273.15$

OUTCOME: Explains thermodynamic systems, properties, Zeroth law of thermodynamics, temperature scales and energy interactions.

FURTHER READING:
- Basic Engineering Thermodynamics, A.Venkatesh, Universities Press, 2008
- Basic and Applied Thermodynamics, P.K.Nag, 2nd Ed., Tata McGraw Hill Pub.
- http://www.nptel.ac.in/courses/112104113/4#

<div align="center">**WORK & HEAT**</div>

OBJECTIVE: Understand various forms of energy including heat transfer and work

STRUCTURE:

> **1.2.1 Work**
> **1.2.2 Other types of work transfer**
> **1.2.3 Heat**
> **1.2.4 Comparison between work and heat**

1.2.1 WORK

1. **Mechanics definition of work**: Work is done when the point of application of a force moves in the direction of the force. The amount of work is equal to the product of the force and the distance through which the point of application moves in the direction of the force. i.e., work is identified only when a force moves its point of application through an observable distance.

<div align="center">Mathematically, $W = \int F.\,dx$</div>

2. **Thermodynamic definition of work**: Work is the energy transfer across the system boundary in an organized manner such that its sole use could be reuced to lift a weight (mass) against gravitational effect.

   Let us consider the battery and the motor as a system. The motor is in turn driving a fan. As the fan rotates, the system (Battery & motor) is doing work upon the surroundings. When fan is replaced by a pulley and a weight, the weight may be raised with the pulley which is driven by the motor. Thus the energy from the system gets transferred to the surrounding in an organized manner and it is utilised to lift the weight against gravitational effect. This energy is called Work.
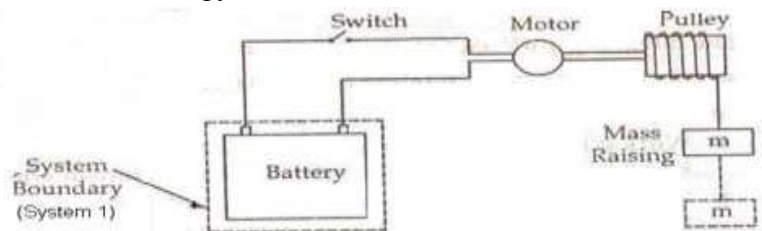
3. Sign convention for Work:
- When work is done by the system, it is arbitrarily taken to be positive.
- When work is done on the system, it is arbitrarily taken to be negative.

Note: 1) **Unit of work is N-m, Joules (J)**

1) **The rate at which work is done by or upon the system is known as power and its unit is J/s or N-m/s or Watts (W)**

4. P.dV work or Displacement Work:

Consider a system which contains a cylinder filled with a gas and a piston moving in the frictionless cylinder as shown in the figure. Let the piston move outward through a small distance 'dx' in time interval 'dt'. Since the piston moves only a small distance, the pressure acting on the face of the piston can be assumed constant.

The infinitesimal (small amount) workdone by the system is

$$\delta W = \text{Force} \times \text{Displacement}$$
$$= (P \times \text{Area of the piston} \times \text{Distance moved by the piston})$$
$$= (P \times A \times dx)$$
$$= (P \times dV) \qquad \{ A \times dx = dV \}$$

$$\delta W = P \times dV$$

If the piston moves through a finite distance, the workdone by the piston is obtained by integrating the above equation between the initial and final state, thus we get

$$\int_1^2 \delta W = \int_1^2 P \times dV = W_{1\text{-}2}$$

If the process proceeds from state 2 to state 1 we can write

$$W_{2\text{-}1} = \int_2^1 \delta W = \int_2^1 P \times dV$$

This equation is applicaple for i) Reversible or frictionless or quasistatic process ii)closed system iii) Effect due to viscous force, magnetic force, gravitational force and electric force are negligible.

5. Point function and Path function:

1) **Point function:** A quantity say 'x' that have a value at every point within its domain of definition or a quantity that depends on the states of the system but not on the path followed by the system is called point function. Its derivative is given by 'dx' and its integral is

$$\int_1^2 dx = x_2 - x_1$$

Example: All intensive and extensive property

2) **Path Function:** A quantity say 'y' , whose value depends on the mathematical path followed by the system to reach from initial state to the final state is called path function. It is an exact differential hence its derivative it is denoted by 'δy'. Thus we can write between two states 1 & 2

$$\int_1^2 \delta y = y_{1-2}$$

6. Prove that work is a path function:

Consider the P-V diagram as shown in the figure. It is possible to reach final state(state 2) from initial state (state 1) or vice versa by following different paths A,B & C. As the area under the curve represents the work for each process, it is evident that the amount of work involved in each process is dependent only on the path followed but not the end points. We can observe that the area under each curve of process is different hence we can conclude that work is a path function. Thus

$$\int_1^2 \delta W = W_{1-2}$$
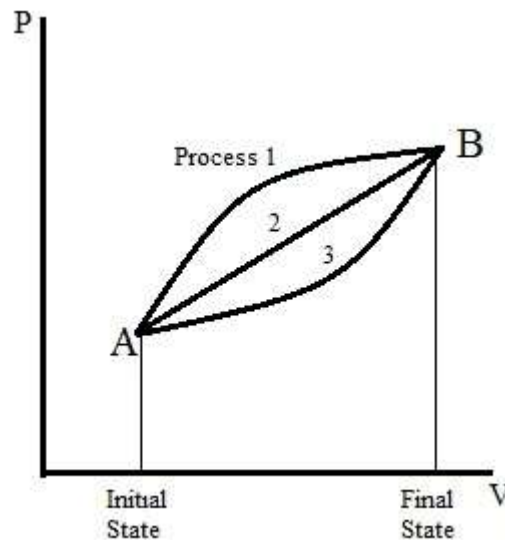
1.2.2 Other Modes of Work:

1) **Shaft Work:** Consider an engine shaft rotated by means of an external force. The shaft undergoes an angular displacement when a constant torque 'T' is applied to it
   Shaft work is given by

$$\delta W = T. d\theta$$

for finite changes shaft work is given by

$$W_{1-2} = \int_{1}^{2} T.\, d\theta$$

Shaft power $= P = \int_{1}^{2} T.\frac{d\theta}{dT} = T.\,\omega$

Where ω = Angular Velocity

2) Electrical Work:

$$I = \frac{dC}{dt}$$

Where dC= Charge in coulombs that cross system boundary in time dt .
Electrical work done by the flow of current is given by

$$\delta W = V.\, dC$$
$$\delta W = V.\, I.\, dt$$

Between two states $W_{1-2} = \int_{1}^{2} VI.$

Electrical Power $= P = V.I$

3) Stretching of a wire:

$$\delta W = -F.\, dL\ldots\ldots\ldots(1)$$

Where , F = External force of tension , dL= Change in length

Stress $= \sigma = \frac{F}{A} = E.\,\varepsilon\ldots\ldots\ldots(2)$

Where, A = Cross sectional area of the wire, E = Modulus of elasticity, ε = Strain

$d\varepsilon = \frac{dL}{L}\ldots\ldots\ldots\ldots(3)$

Substituting 2,3 in 1 we get

$$\delta W = -A.\, E.\, L.\,\varepsilon.\, d\varepsilon$$

For finite changes in length

$$W = -A.\, E.\, L \int_{1}^{2} \varepsilon.\, d\varepsilon = \frac{-A.\, E.\, L}{2}\, (\varepsilon^2 - \varepsilon^1)$$

4) **Surface film work or stretching liquid film:**
   workdone by the wire frame is given by
   $\delta W = -\sigma_s. dA$
   σ_s = Surface tension of a film, dA = Change in area

   for finite changes, $W = -\int_1^2 \sigma_s. dA$

5) **Flow work:** work is needed to push the fluid into or out of the boundary of a control volumeif mass flow is involved. This work is called the flow work (flow energy). Flow work is necessary for maintaining a continuous flow through a control volume.

   Consider a fluid element of volume V, pressure P, and cross sectional area A as shown in figure. The flow immediately upstream will force this fluid element to enter te control volume, and it can be regarded as an imaginary piston. The force applied on the fluid element by the imaginary piston is F = P. A.
   The work done due to pushing the entire fluid element across the boundary into the control volume is
   $W_{Flow} = F.L = P.A.L = P.V$
   For unit mass = $w_{flow} = P.v$
   $W_{Flow\ in} = W_{Flow\ out}$
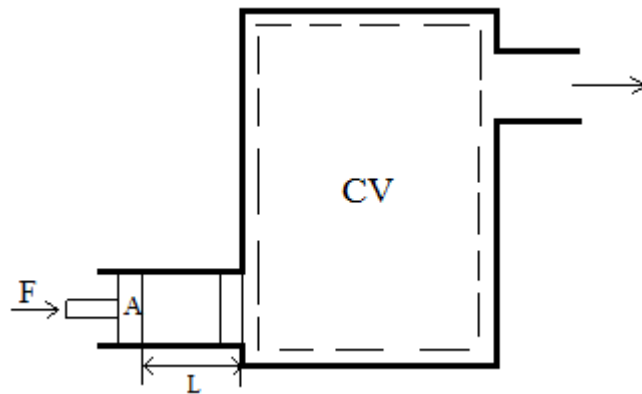
6) **Stirring Work:**
   $\delta W = T. d\theta$
   If 'm' is the mass of the weight lowered through a distance 'dZ' , then
   $\delta W = T. d\theta = m. g. dZ$
   For finite variation we have,

$$W_{1-2} = \int_1^2 m.\,g.\,dZ$$

Special Cases:

1) **Restricted or Resisted expansion:**

Consider any piston cylinder machine. During expansion of the fluid, the fluid pressure remains uniform throughout the cylinder against a slow moving piston. Such process is called restricted expansion.

The work delivered at the output shat can be determined by using the equation

$$W = a.\,S.\frac{V_S}{L} = P_m.\,V_S$$

Where, a = Area of the indicator diagram of Length 'L'

S = Spring number

V_S = Swept volume

P_m = Mean effective pressure

If 'N' is the revolutions per second we have power developed = $P = P_m.L.A.N$

2) **Unrestricted Expansion:**

Consider a rigid vessel divided by a light diaphragm. One compartment formed by the diaphragm contains a gas whereas the other compartment is evacuated. When the diaphragm is ruptured, the gas moves towards the evacuated compartment. Due to this there will be a change in volume . The process is not reversible even though the initial and final states are in equilibrium. Since vaccum offers no resistance to expansion, the process doesn't pass through equilibrium states and hence there will no well-defined path inturn work transfer will be zero.

Before Rupture

After Rupture
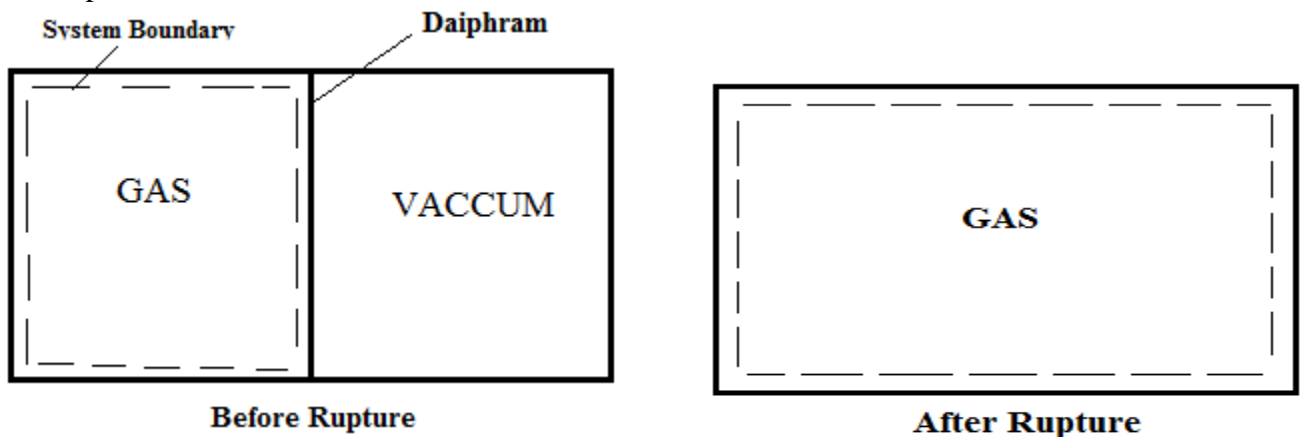
1.2.3 HEAT:

Heat is defined as the form of energy that is transferred between two systems or between system and its surroundings by virtue of a temperature difference.

➢ **Adiabatic process:** A process during which there is no heat transfer is called an adiabatic process (Q =0)

Note: Although heat transfer is not there in adiabatic system, The Temperature of a system may change due to work transfer in adiabatic system.

➢ **Diathermic wall:** A wall which is permeable to heat flow is a diathermic wall.
➢ **Adiabatic wall:** A wall which is impermeable to heat flow is adiabatic wall.

Sign Convention for Heat:

- Heat transfer into the system is considered as **positive.**
- Heat transfer from the system is considered as **negative.**
- Unit of Heat transfer(Q) is **KJ**
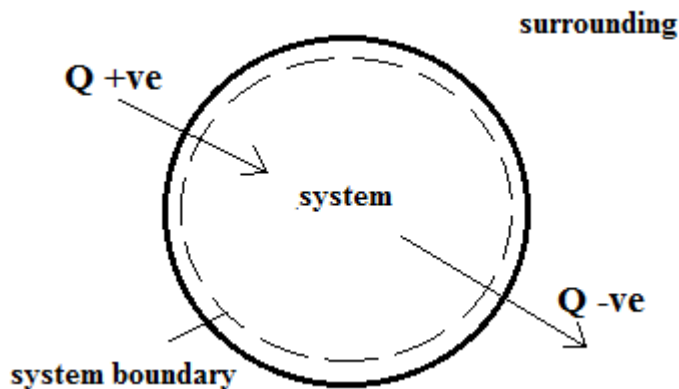
Modes of Heat Transfer:

1) **Conduction:** Heat transfer due to direct contact between the elementary particles of a body that is molecules, atoms, free electrons.
2) **Convection:** Heat transfer from one body to another by the moving particles of liquid , gas or loose solids during their relative motion in space.
3) **Radiation:** Heat transfer by electromagnetic waves through a medium which is transparent to thermal radiation. Fraction of the internal energy of a hot body is converted into radiant energy changing in the form of heat.

Heat is a Path Function:

Similar to work the amount of heat transferred from state 1 to state 2 depends on the path of the system. The area under different process is different hence the amount of heat transfer also varies. Hence for a quasi-static process heat transferred is written as

$$\int_{1}^{2} \delta Q = Q_{1-2} = \int_{1}^{2} T.\,dS$$

Where, S = it is an extensive property called Entropy
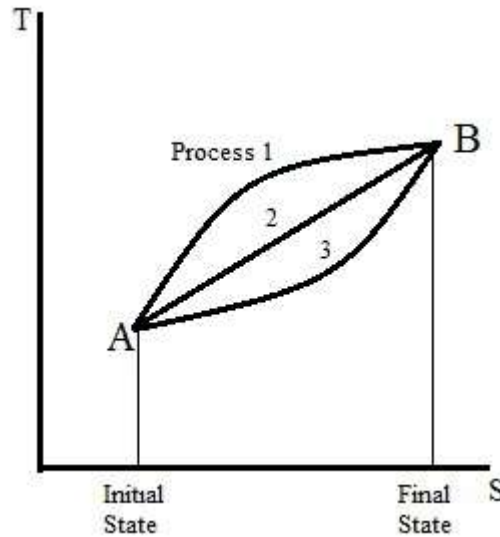
1.2.4 Comparison between work and heat:

Similarities:

1. Both are path functions and inexact differentials.
2. Both are boundary phenomenon i.e., both are recognized at the boundaries of the system as they cross them.
3. Both represent transient phenomenon; these energy interactions occur only when a system undergoes change of state i.e., both are associated with a process, not a state. Unlike properties, work or heat has no meaning at a state.
4. A system possesses energy, but not works or heat.

Dissimilarities:

1. Heat is energy interaction due to temperature difference only; work is by reasons other than temperature difference.
2. In a stable system, there cannot be work transfer; however there is no restriction for the transfer of heat.
3. The sole effect external to the system could be reduced to rise of a weight but in the case of a heat transfer other effects are also observed.
4. Heat is a low grade energy whereas work is a high grade energy.

IMPORTANT THEORY QUESTIONS:
1. Define work from thermodynamic point of view and derive an expression for flow work.
2. What are the similarities and dissimilarities between work and heat.
3. Show that work and heat are path fuction
4. Derivean expression for displacement work or P.dV work for a quasistatic process.
5. Explain briefly a quasistatic process and displacement work.
6. Explain With an example how thermodynaim work is different from mechanics definition of work
7. Specify the most widely used sign convention for work & Heat inetraction.
8. Does heat transfer inevitable cause a temperature rise, what is the other cause for rise in temperature.

PROBLEMS:
1. The piston of an oil engine, of area $0.0045m^2$ moves downwards 75mm, drawing $0.00028m^3$ of fresh air from the atmosphere. The pressure in the cylinder is uniform during the process at 80kPa, while the atmospheric pressure is 101.375 kPa, the difference being due to the flow resistance in the induction pipe and the inlet valve. Estimate the displacement work bdone by the air.
2. A cylinder contains one Kg of fluid at an initial oressure of 20bar . The fluid is allowed to expand reversible behind a piston according to law $PV^2 = C$ until the volume is doubled. The fluid is then cooled reversibly with the piston firmly locked in this position until the pressure rises to the original value of 20bar. Calculate the net work done by the fluid for an initial volume of $0.05m^3$.
3. A fluid contained in a horizontal cylinder fitted with a frictionless leak proof piston is continuously agitated by a stirrer passing through the cylinder cover. The diameter of the cylinder is 40cm and the piston is held against the fluid due to atmospheric pressure equal to 100kPa. The stirrer turns 700 revolutions with an average torque of 1Nm. If the piston slowly moves outwards by 50cm determine the net work transfer to the system.
4. A spherical balloon has a diameter of 20cm and contains air at 1.5bar. The diameter of the balloon increases to 30cm in a certain process during which pressure is proportional to the diameter. Calculate the work done by the air inside the balloon during the process.
5. A balloon of flexible material is to be filled with air from a storage bottle untill it has a volume $0.7m^3$. The atmospheric pressure is 1.013bar. Determine the workdone by the system comprising the air initially in the bottle,given that the ballon is light and requires no strtching.

   Solution: $W_d = \int_{balloon} P_b.dV + \int_{Bottle} P_b.dV$

   $= P_{atm} \int dV + 0$ { No change in volume of the bottle hence Zero}

   $= 1 \times (0.7-0) \times 100 = 70$ KJ

Problems :-

1) An engine cylinder has a piston of area $0.12 m^2$ & contains gas at a pressure of $1.5 MPa$. The gas expands according to a process which is represented by a straight line on p-v diagram. The final pressure is $0.15 MPa$. Determine the magnitude & direction of work transfer if the piston stroke is $0.30m$

→ Given   A of Piston $= 0.12 m^2$
$P_1 = 1.5 MPa$
$P_2 = 0.15 MPa$
$L = 0.30 m$
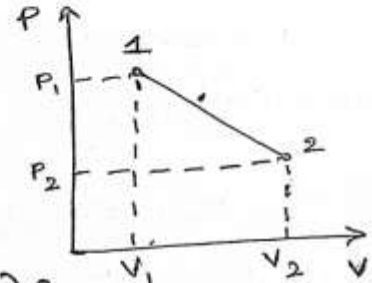
Workdone $= {}_1W_2 = W_{1-2} =$ Area under the curve 1-2

$= \frac{1}{2}(V_2-V_1)(P_1-P_2) + (V_2-V_1)P_2$

$= (V_2-V_1)\left[\frac{P_1}{2} - \frac{P_2}{2} + P_2\right]$

$W_{1-2} = \frac{1}{2}(P_1+P_2)(V_2-V_1) = \frac{1}{2}[1.5+0.15]\times1000\times(0.12+0.3)$

$\boxed{W_{1-2} = 594 \ KJ}$ +ve hence work is done by the System //

$= 2$

2) An ideal gas contained within a cylinder with a movable piston as shown in fig. Evaluate the work per unit mass by the gas for the path indicated in the system. Assume known conditions at state 1 & 3

${}_1W_3 = \int_1^3 P \cdot dV = \int_1^2 P \cdot dV + \int_2^3 P \cdot dV$

$= P_1(V_2-V_1) + P_3 V_3 \ln\left(\frac{V_3}{V_2}\right)$

$V_2 = \frac{RT_2}{P_2} = \frac{RT_3}{P_2} = \frac{RT_3}{P_1}$

3) A spherical balloon of 1m diameter contains a gas at 250 kpa and 300K. The gas inside the balloon is heated until the pressure reaches to 500kpa. During the process of heating, the pressure of gas inside the balloon is proportional to the diameter of the balloon. Calculate the workdone by the gas inside the balloon.

→ Given :- $D = 1m$

$\qquad P_1 = 250 \, kpa$

$\qquad T_1 = 300 \, K$

$\qquad P_2 = 500 \, kpa$

$\qquad P \propto D$

$\qquad {}_1W_2 = ?$

As pressure is proportional to diameter of the balloon

$P \propto D$

$P = CD$ where 'C' is a constant → ①

Substituting given values in equation ①

$\qquad 250 = C \times 1$

$\qquad \therefore C = 250 \, kpa/m$

Now $\qquad P_2 = C \cdot D_2$

$\qquad 500 = 250 \times D_2$

$\qquad \therefore D_2 = 2m$

Volume of the balloon is given by

$\qquad V = \dfrac{\pi}{6} D^3 \rightarrow$ ② $\left\{ V = \dfrac{4}{3}\pi r^3 \right\}$ volume of sphere

differentiating equ② we get

$\qquad dV = \dfrac{\pi}{6} \times 3D^2 = \dfrac{\pi}{2} \cdot D^2 \, dD$

work done = ${}_1W_2 = \displaystyle\int_1^2 P \cdot dV = \int_1^2 CD \times \dfrac{\pi}{2} D^2 \cdot dD = \int_1^2 \dfrac{\pi}{2} \cdot C \cdot D^3 \cdot dD$

$\qquad {}_1W_2 = \dfrac{C\pi}{8}\left(D_2^4 - D_1^4\right) = \dfrac{\pi \times 250}{8}\left(2^4 - 1^4\right)$

$\qquad \boxed{{}_1W_2 = 1472.63 \, kJ}$

1) Consider the system shown in fig. Initial conditions, of the gas are $V_1 = 0.1m^3$ & $P_1 = 200kpa$. The ambient atmospheric pressure is 100kpa. The spring exerts a force which is proportional to the displacement from its equilibrium position. The gas is heated until the volume is doubled at which point $P_2 = 600kpa$. Determine the work done by the gas.

→ Force balance at any position

Total press force acting on system = Force due to atmospheric air + Force due to the spring
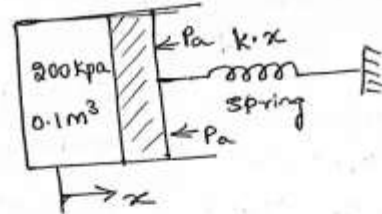
$$p \cdot A = P_a \cdot A + \vec{k} \cdot x \qquad \{ \because F \propto x \Rightarrow F = k \cdot x \}$$

Displacement $= x = \dfrac{Volume(V)}{Area(A)}$

$$\therefore \quad p \cdot A = P_a \cdot A + k \cdot \dfrac{V}{A}$$

$$\boxed{P = P_a + k \cdot \dfrac{V}{A^2}} \quad *** \Rightarrow \textcircled{1}$$

Work done is given by $_1W_2 = \displaystyle\int_1^2 P \cdot dV = \int_1^2 \left\{ P_a + k \cdot \dfrac{V}{A^2} \right\} \cdot dV$

Given
$P_1 = 200 \, Kpa$
$V_1 = 0.1 m^3$
$P_2 = 600 \, kpa$
$V_2 = 2V_1 = 0.2m^3$

$$_1W_2 = \int_1^2 P_a \cdot dV + \int_1^2 k \cdot \dfrac{V}{A^2} \cdot dV$$

$$_1W_2 = P_a (V_2 - V_1) + \dfrac{k}{A^2} \times \left[\dfrac{V_2^2 - V_1^2}{2} \right]$$

$$_1W_2 = P_a (V_2 - V_1) + \dfrac{k}{2A^2} \left[(V_2 + V_1)(V_2 - V_1) \right]$$

$$_1W_2 = (V_2 - V_1) \left[P_a + \dfrac{k}{2A^2} (V_2 + V_1) \right]$$

from equation (1) $\quad k \cdot \dfrac{V}{A^2} = (P - P_a)$

at state 1 we can write $\dfrac{k \cdot V_1}{A^2} = P_1 - P_a$

at state 2 we can write $\dfrac{k \cdot V_2}{A^2} = P_2 - P_a$

$$\therefore \quad _1W_2 = (V_2 - V_1) \left[P_a + \dfrac{P_2 - P_a}{2} + \dfrac{P_1 - P_a}{2} \right]$$

$$_1W_2 = (V_2 - V_1) \left[\dfrac{P_1 + P_2}{2} \right] = (0.2 - 0.1) \left[\dfrac{200 + 600}{2} \right] = 40KJ$$

5) A piston & cylinder machine containing a fluid system has a stirring device as shown. The piston is frictionless, & it is held down against the fluid due to atmospheric pressure of 101.3 kpa. The stirring device is turned 9500 revolutions with an average torque against the fluid of 1.25 N·m. Meanwhile the piston of 0.65m diameter moves out 0.6m. Find the net work transfer of the system.

→ Work done by the stirring device upon the System = Shaft work

$T = F \cdot r$

$S = 2\pi r \cdot N$

$W_{sh} = F \cdot S = 2\pi NT = W_1$

$W_1 = 2 \cdot \pi \cdot 9500 \cdot 1.25 = 74622 \ N \cdot m$

$\boxed{W_1 = 74.622 \ KJ}$ negative work ∵ done on system

Work done by the System upon the surroundings

$W_2 = F \cdot L = p \cdot A \cdot L$
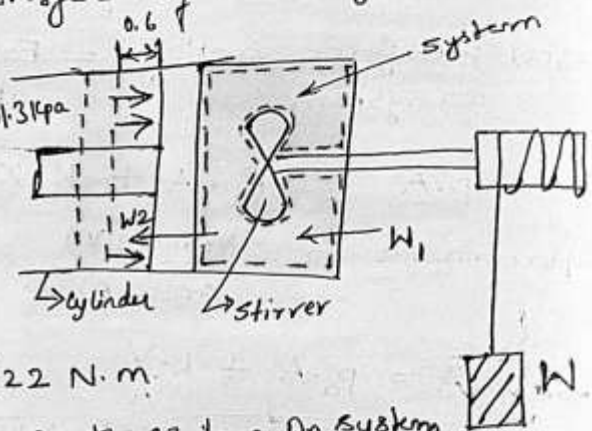
where, $p = 101.3 \ kpa$, $A = \frac{\pi}{4} \times (0.65)^2 = 0.3318 \ m^2$, $L = 0.6 \ m$

$W_2 = 101.3 \times 0.3318 \times 0.6 = 20.167 \ KJ$ +ve work

Hence Net work transfer for the system

$W_{net} = W_1 + W_2 = -74.622 + 20.167$

$\boxed{W_{net} = -54.455 \ KJ}$

→A fluid undergoes the following processes in sequence to complete a cycle. i)-Heated reversibly at P.C of 1.05 bar untill it has a volume of 0.02 m³ ii) It is then compressed reversibly according to a law $pv = c$ to a pressure of 42 bar iii) It is then allowed to expand reversibly according to a law $p.v^{1.3} = c$. iv) Finally it is heated at constant volume back to initial conditions.
If the work done during the constant pressure process is 515 N-m , calculate the net work done on or by by the cycle. Sketch the cycle on p-v diagram.
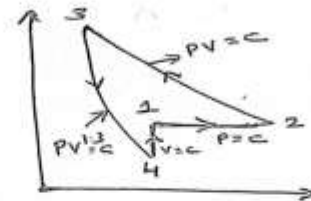
Solution :- Given

$$_1W_2 = 515 \ N \cdot m$$

$$P_1 = P_2 = 1.05 \ bar = 1.05 \times 10^5 \ pa$$

$$P_3 = 4.2 \ bar = 4.2 \times 10^5 \ pa$$

$$V_2 = 0.02 \ m^3$$

work done during $P = c$ (1-2) process

$$_1W_2 = P_1(V_2 - V_1) \Rightarrow 515 = 1.05 \times 10^5 (0.02 - V_1)$$

$$V_1 = 0.015 m^3 = V_4$$

To find $_2W_3 = P_2 V_2 \ln\left(\frac{V_3}{V_2}\right)$.

$V_3 = ?$

To find V_3 , we know that for constant temp process

$$V_3 = \frac{P_2 V_2}{P_3} = \frac{1.05}{4.2} \times 0.02 = 5 \times 10^{-3} m^3$$

∴ $_2W_3 = 1.05 \times 10^5 \times 0.02 \ \ln\left(\frac{5 \times 10^{-3}}{0.02}\right) = -2911.2 \ J$

To find $_3W_4 = \frac{P_3 V_3 - P_4 V_4}{n-1}$

to find P_4 for an polytropic process

$$\frac{P_3}{P_4} = \left(\frac{V_4}{V_3}\right)^{1.3} \Rightarrow P_4 = 0.998 \ bar$$

∴ $_3W_4 = \frac{(4.2 \times 5 \times 10^{-3} - 0.998 \times 0.015) \times 10^5}{1.3 - 1} = 1976.78 \ J$

Net work done = $W_{net} = {_1W_2} + {_2W_3} + {_3W_4} + {_4W_1} = -419.5 \ J$

List of Formulas:

1. Displacement work $= W_{1-2} = \int_1^2 P.\,dV$

2. Workdone and heat Transfer equation for different processes

- **Constant Volume Process or Isobaric Process (P/T = Const)**

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

$W_{1-2} = 0$

$Q_{1-2} = m(u_2 - u_1) = mC_V (T_2 - T_1)$

$du = C_V/dT$

- **Constant Pressure Process (V/T = Const)**

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

$W_{1-2} = 0$

$Q_{1-2} = m(h_2 - h_1) = mC_p (T_2 - T_1)$

$dh = C_p/dT$

- **Constant Temperature Process (PV = Const)**

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}$$

$$W_{1-2} = P_1 V_1 \ln \frac{V_2}{V_1} = P_2 V_2 \ln \frac{V_2}{V_1}$$

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

- **Adiabatc Process(PV$^\Upsilon$ = Const)**

$P_1 V_1{}^\Upsilon = P_2 V_2{}^\Upsilon$

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$$

$Q_{1-2} = 0$

For Adiabatic process only you can use following formulas

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

OUTCOME: Interelation between heat and work . concept of work and different types of work.

FURTHER STUDY :

- Basic Engineering Thermodynamics, A.Venkatesh, Universities Press, 2008

- Basic and Applied Thermodynamics, P.K.Nag, 2nd Ed., Tata McGraw Hill Pub.
- http://www.nptel.ac.in/courses/112104113/4#