

LECTURE NOTES ON

ELEMENTS OF MECHANICAL ENGINEERING

PREPARED BY ACHYUT KUMAR PATRA

DEPARTMENT OF MECHANICAL ENGINEERING

B.O.S.E Cuttack

THERMODYNAMICS

(Chapter - 1)

Defⁿ

→ Thermodynamics is the branch of science which deals with the study of energy interaction between system and surrounding and its effect on properties of system.

Thermo - Dynamics

Energy

Interaction / Transformation / motion etc.

Stored

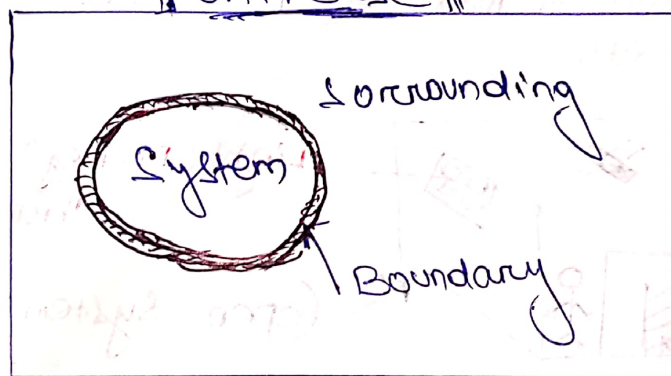
Transition

Potential Energy) P.E. (mgh)
(Kinetic Energy) K.E. ($\frac{1}{2}mv^2$)
(Internal Energy) I.E.

Heat
Work

$$\text{Total energy} = \text{I.E.} + \text{P.E.} + \text{K.E.} \\ = U + mgh + \frac{1}{2}mv^2$$

Universe



* Size of universe depends upon system as well as surrounding

System: → Anything under consideration / study Based upon

Surrounding: → Anything external to system.

Boundary: → which differentiate in between system and surrounding

Note

Two types

i) Fixed ii) moveable

- ⊕ Boundaries are real or can be imaginary
- ⊕ A system's max^m energy dissipation range / effect is known as boundary

System + surrounding → universe

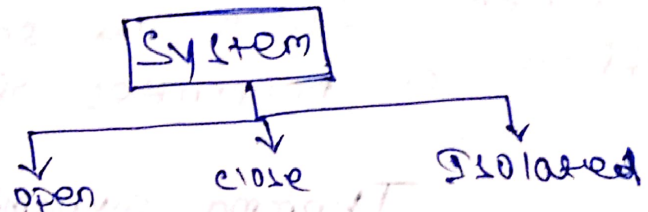
Q. What do you mean by Thermodynamic System?

→ Thermodynamic system is a volume of space containing the item chosen for thermodynamic analysis.

Types of system:

3 types:

- ① open system
- ② close system
- ③ Isolated system.

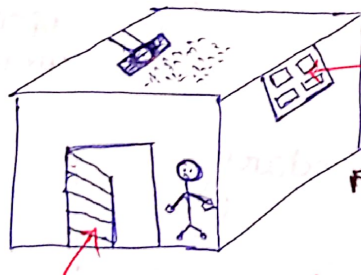


open system

→ A system is said to be open if both the mass and energy interaction between system and surrounding occurs.

mass → It is the amount of matter contained in a body.
→ The value of mass does not change w.r.t. the position.

Unit: kg, gm etc.



Light (Energy) can go outside through skylight

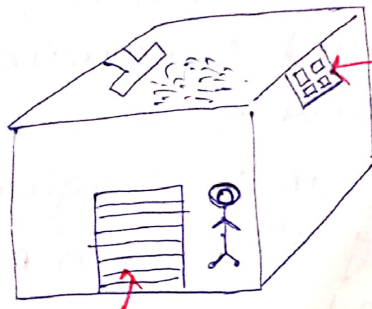
(open system)

Door is open, so man (mass) can go outside

e.g. compressor, Turbine, nozzle etc.

close system

→ A system is said to be close if there is only energy interaction occurs, there is no mass trans ~~formation~~ / Interaction occurs.



Light (Energy) can go outside through skylight

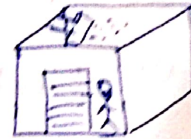
Door is closed so man (mass) can't go outside

e.g. Thermal power plant

Isolated System:

→ A system is said to be Isolated if there is neither mass nor energy interaction/transfer occurs between system and surroundings.

e.g. (i) well insulated flask
(ii) universe etc.



(No energy & mass can go outside)

Approaches to study a system:

Microscopic

→ Individual molecules is taken into consideration

→ It is also known as Statistical Thermodynamics

Macroscopic

→ overall or on an average behaviour of molecules are taken into consideration.
→ It is also called classical Thermodynamics.

Thermodynamic properties of a system:

→ Any quantifiable characteristics of the system which can be measured are known as Thermodynamic properties.

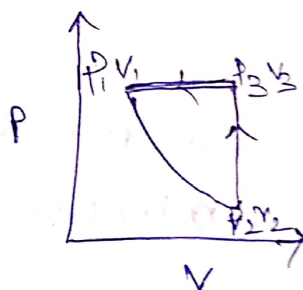
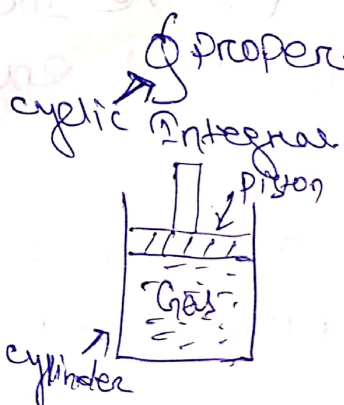
e.g. pressure, Temp., volume, entropy, enthalpy etc.

Note colour, smell, tastes are not the properties.

→ properties are point function / state function.

→ properties are independent of past history

→ properties are exact differentials. (Cyclic integral of any variable is zero)



If $\oint dP = 0$
 $\oint dV = 0$ } Then it is called exact differentials

Classification of Thermodynamic properties:

The thermodynamic properties of a system may be divided into the following two types:

- i) Intensive
- ii) Extensive

Note:

→ The characteristics which can be used to describe the conditions of physical existence of the system are known as properties.

Intensive:

→ Intensive properties are those properties, which are independent of mass. i.e. Intensive properties do not depend on the amount of matter in a sample.

- eg
- i) Temperature
 - ii) pressure
 - iii) Density
 - iv) viscosity

Extensive:

→ Extensive properties are those properties which depends on the mass i.e. the matter present in the sample or object

eg

- i) Mass
- ii) volume
- iii) weight
- iv) Energy
- v) Enthalpy
- vi) Entropy

→ In other words The properties of the system, whose value for the entire system is equal to the sum of their values for the individual parts of the system are called extensive properties.

→ Total volume, Total mass, Total energy of a system are its extensive properties.

Note:

(i) The ratio of any extensive property of a system to the mass of the system is called an average specific value of the property.

* All the specific ~~permed~~ properties are Intensive property

e.g. Specific volume = $\frac{\text{Volume}}{\text{mass}}$
Specific enthalpy = $\frac{\text{Enthalpy}}{\text{mass}}$



let's say $V = 1 \text{ m}^3$
 $\text{mass} = 1000 \text{ kg}$

$$\text{Specific volume} = \frac{V}{m} = \frac{1}{1000} = 0.001 \text{ m}^3/\text{kg}$$

i.e. each 1 kg , ~~mass~~ contains 0.001 m^3 volume of water.

(ii) The ratio of two extensive properties are always Intensive property

e.g. Density = $\frac{\text{mass} \leftarrow \text{extensive}}{\text{volume} \leftarrow \text{extensive}}$
Intensive

Point function (Exact differential)

→ The properties of a system which does not depend upon on path of the process, but depends on states (two end condition of process) this property is called point function.

→ Thermodynamic properties are point function is independent of the path and depends only on initial and final states of the system.

e.g. pressure, temp., volume etc.

Path function (Inexact differential)

→ There are certain quantities which cannot be located on a graph by a point but are represented by the area on that graph.

→ Those quantities are dependent on the path of the process and are called path function.

e.g. work and heat

Q. Define Heat and work?

→ Heat (Q) is a form of energy that is transferred from one body to another as the result of a difference in Temp.

→ Heat energy is a form of energy transfer, unlike temperature, which refers to the energy contained within a system, heat refers to the transfer of that energy between systems and surroundings.

→ Heat shows the variation of temp. across the systems and Temp. is a lensitional property of a body.

→ The direction of heat transfer from higher temp. to lower temp.

Unit: Joule (J) or Kilo-Joule (KJ)

Work (~~Physics~~) (mechanics) (W)

→ Work is the energy transferred to or from an object via the ~~force~~ application of force along a displacement.

→ It is the product of force and the displacement in the direction of force.

$$\text{Work} = \text{Force} \times \text{displacement}$$

Unit: N-m, or Joule (J),
(Newton-metre)

Thermodynamic work

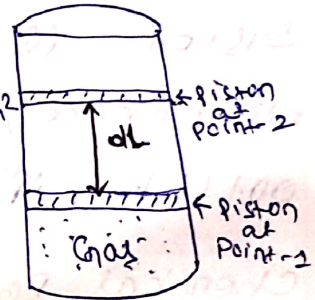
→ Thermodynamic work refers to the transfer of energy across the boundary of the system other than due to temp. difference

→ Energy Transfer which is not because of temp difference is called work.

Define

Area of the cross section of cylinder = $a \text{ m}^2$
pressure of piston = P

Gas expand/displacement = dL



we know

$$\text{Force} = \text{Pressure} \times \text{Area} \\ = P \times a$$

work done by gas = Force $\times$ displacement

$$\delta W = P \times a \times dL$$

Small amount of work

(Note: $a \times dL = dV$ represent small increase volume of gas)

$$\text{So, } \delta W = P \times dV$$

$$\Rightarrow \int \delta W = \int P dV$$

$$\Rightarrow W = \int_{V_1}^{V_2} P dV$$

} when piston expands V_1 is the initial volume of gas and V_2 is the final volume of gas

$$\Rightarrow W = P \int_{V_1}^{V_2} dV$$

$$\Rightarrow W = P (V_2 - V_1)$$

$$\Rightarrow \boxed{W = P \cdot \Delta V}$$

} unit = $\text{N} \cdot \text{m}$ or J

Note:

The thermodynamic work may be defined by the energy transfer due to the change in volume of the system due to the application of pressure. (Pressure may be internal or external)

Thermodynamic Equilibrium States:

→ A system is said to be in Thermodynamic Equilibrium if simultaneously it is in mechanical equilibrium, thermal equilibrium and chemical equilibrium.

mechanical Equilibrium: (Equality of force, pressure etc)

→ In mechanical equilibrium pressure inside the system is throughout uniform (i.e. no pressure difference) and it is equal to the pressure outside, if boundary is flexible.

chemical Equilibrium: (chemically inactive i.e. no reaction is happening)

→ When there is no spontaneous change of internal structure with the effect of any chemical reaction or transform of matter from one part of the system to another i.e. diffusion.

Thermal Equilibrium: (Temp. same)

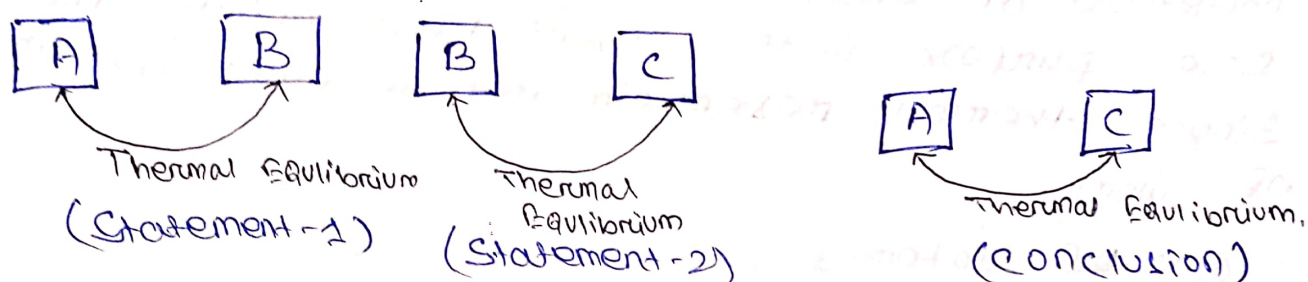
→ When there is no temp. gradient (temp. diff.) within interior of system or system and surroundings.

condition: If system boundary is not well insulated.

Law's of Thermodynamics :

* Zeroth Law : (Fundamental Law)

→ If two bodies A & B are in thermal equilibrium and body B is in thermal equilibrium with another body C separately, then body A and C will also be in Thermal equilibrium.



→ This law gives the concept of Temperature

* First Law of Thermodynamics

→ The First law of thermodynamics is also known as Law of conservation of energy which states, The energy can neither be created nor destroyed, through it can be ~~transferred~~ transformed from one to another form.

→ According to this Law, the total heat energy is equal to the sum of Internal energy and total work done by the system.

$$\Delta Q = \Delta U + \Delta W$$

→ First law of thermodynamics is the consequence of conservation of energy

* For a closed system, undergoing cyclic process, net Heat interaction is equal to the net work interaction,

$$\begin{aligned} \sum Q &= \sum W \\ \text{or } \oint dQ &= \oint dW \\ \sum Q &= Q_{in} - Q_{out} \\ \sum W &= W_{out} - W_{in} \end{aligned}$$

* Second Law of Thermodynamics :

→ The second law of Thermodynamics may be defined in many ways, but the two common statements according to Kelvin-Planck and Clausius are as follows:

Kelvin, Planck's statement:

→ According to Kelvin Planck "It is impossible to construct an engine working on a cyclic process, whose sole purpose is to convert heat energy from a single thermal reservoir into an equivalent amount of work."

Clausius statement:

→ According to Clausius statement "It is impossible for a self acting machine, working in a cyclic process, to transfer heat from a body at a lower temperature to a body at higher temperature without the aid of an external agency/energy."

Sign convention for Thermodynamic Heat, Internal energy and work:

Heat:

Heat is added to the system → +ve sign
Heat is rejected from the system → -ve sign.

Internal Energy:

Temp. rise → Internal Energy increases ↑ (+ve)
Temp. drop → Internal Energy decreases ↓ (-ve)

Work

Work done By the system → +ve work
Work done on the system → -ve work

Laws of Perfect gases

Perfect gas:

→ perfect gas may be defined as a state of a substance, whose evaporation from its liquid state is complete.

(Liquid) → complete evaporation → perfect gas
→ partial evaporation → vapour.

→ In actual practice no such Perfect/Ideal gas exist, so superheated vapour may be considered as perfect gas. In reality Real gas exist.

→ An Ideal/perfect gas strictly obeys all the gas laws under all conditions of temperature and pressure.

→ In Ideal gas the attraction forces between the molecules is ^{Almost} zero (negligible) and the molecules of Ideal gas have negligible volume.

→ A real gas behaves like an Ideal gas at High Temp. and Low pressure.

Note:

If we increase pressure the molecules of the Ideal gas may come closer, so in order to overcome this we have to keep low pressure and in case of Temp., the rise in temp. causes the molecules to move far away from each other.

→ The real gases which are ordinarily difficult to liquify, such as oxygen, nitrogen, hydrogen and air, within certain temp. and pressure limits may be regarded as perfect gases.

Laws of perfect Gases:

→ The physical properties of a gas are controlled by the following three variables:

- ① pressure exerted by the gas.
- ② volume occupied by the gas.
- ③ Temp. of the gas.

→ The behaviour of a perfect gas, undergoing any change in the above mentioned variables, is governed by the following laws which have been established from experimental results.

① Boyle's law:

→ This law was formulated by Robert Boyle in 1662. It states, "The absolute pressure of a given mass of a perfect gas varies inversely at its volume, when the temperature remains constant."

mathematically,

$$P \propto \frac{1}{V} \quad \left\{ \text{Temp. constant} \right\}$$

$$\text{or } PV = C$$

for various states / conditions $P_1 V_1 = P_2 V_2 = P_3 V_3$.

② Charles's Law:

→ This law was formulated by a Frenchman Jacques A.C. Charles in about 1787. It may be stated by the following two different forms:

Statement - 1

⑤ The volume of a given mass of a perfect gas varies directly as its absolute temp. when the absolute pressure remains constant mathematically,

$$V \propto T \quad \left\{ \text{pressure constant} \right\}$$

$$\text{or } \frac{V}{T} = C$$

for various conditions, $\frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V_3}{T_3} = \dots$

Statement - 2

⑥ "All perfect gases change in volume by $\frac{1}{273}$ th of its original volume at 0°C for every 1°C change in temp. when the pressure remains constant

Let, $V_0 \rightarrow$ volume of the given mass of gas at 0°C
 $V_t \rightarrow$ volume of the same mass of gas at $t^\circ\text{C}$

Then, According to the above statement:

$$V_t = V_0 + \frac{1}{273} V_0 \times t =$$

$$= V_0 \left(\frac{t}{273} + 1 \right) = V_0 \left(1 + \frac{t}{273} \right)$$

$$= V_0 \left(\frac{273 + t}{273} \right)$$

$$= V_0 \times \frac{T}{T_0}$$

$T \rightarrow$ Absolute temp. corresponding to $t^\circ\text{C}$.

$T_0 \rightarrow$ Absolute temp. corresponding to 0°C .

→ A little consideration will show that, the volume of a gas goes on decreasing by $\frac{1}{273}^{\text{th}}$ of its original volume for every 1°C decrease in temp. It is thus obvious, that at a temp. of -273°C , the volume of the gas would become zero.

* The temp. at which the volume of a gas become zero is called Absolute zero temp.

General Gas equation:

→ In Boyle's law and Charles's law we have seen that it gives us the relation between the two variables when the third variable is constant. But in actual practice, all the three variables i.e. pressure, volume ^{and} temp. change simultaneously. In order to deal with this (all the practical cases) the Boyle's law and Charles's law are combined together.

Boyle's Law:

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

Charles's law:

$$V \propto T$$

combining these two law we get

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

$$\Rightarrow PV \propto T$$

$$\Rightarrow PV = CT \quad \left(\begin{array}{l} \text{constant is multiplied to} \\ \text{remove} \\ \text{system} \end{array} \right) \text{proportional (Q1)}$$

$$\Rightarrow \frac{PV}{T} = C$$

For different conditions:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3} = \dots = C$$

Q. A gas occupies a volume of 0.1 m^3 at a temp. of 20°C and a pressure of 1.5 bar . Find the final temp. of the gas, if it is compressed to a pressure of 7.5 bar and occupies a volume of 0.04 m^3 .

Soln

$$V_1 = 0.1 \text{ m}^3$$

$$T_1 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$$

$$P_1 = 1.5 \text{ bar} = 1.5 \times 10^5 \frac{\text{N}}{\text{m}^2}$$

$$P_2 = 7.5 \text{ bar} = 7.5 \times 10^5 \frac{\text{N}}{\text{m}^2}$$

$$V_2 = 0.04 \text{ m}^3$$

$$T_2 = ?$$

we know that,

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\Rightarrow \frac{1.5 \times 10^5 \times 0.1}{293} = \frac{7.5 \times 10^5 \times 0.04}{T_2}$$

$$\Rightarrow T_2 = \frac{7.5 \times 0.04 \times 293}{1.5 \times 0.1} = 586$$

$$\Rightarrow T_2 = 586 \text{ K}$$

$$\text{or } T_2 = 586 - 273 = 313^\circ\text{C}$$

Ans

Characteristic Equation of a Gas

→ It is a modified form general gas equation. If the volume (V) in the general gas equation is taken as that of 1 kg of gas (known as specific volume $\left\{\frac{V}{m}\right\}$)

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

denoted by V_s , then the constant c (in the general gas equation) is represented by another constant R (in the characteristic equation of Gas)

So, the general gas equation may be rewritten as,

$$P V_s = R T$$

volume per unit mass
or

Volume of 1 kg mass of gas

R = characteristic gas constant

$$(R) = 287 \text{ J/kg K} \quad \text{or} \quad 0.287 \text{ kJ/kg K}$$

Atmospheric Air

for any mass m kg of a gas, the characteristic gas becomes,

$$m \cdot P V_s = m R T$$

$$\Rightarrow P V = m R T$$

or

characteristic gas equation
Ideal Gas equation

$$P = \frac{m}{V} R T$$

$$\Rightarrow P = \rho \cdot R T$$

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

$$\Rightarrow \rho = \frac{m}{V}$$

Note:

① The unit of gas constant (R) is different for different gases. In S.I. units, its value for atmospheric Air is taken 287 J/kg K or 0.287 kJ/kg K

Unit calculation

$$PV = mRT$$

$$2) R = \frac{PV}{mT} = \frac{\frac{\text{N}}{\text{m}^2} \times \text{m}^3}{\text{kg} \cdot \text{K}} = \frac{\text{N} \cdot \text{m}}{\text{kg} \cdot \text{K}} = \text{J/kg K}$$

($1 \text{ N} \cdot \text{m} = 1 \text{ J}$)

Gay - Lussac Law :

→ This law states that "The absolute pressure of a given mass of a perfect gas varies directly as its absolute temperature, when the volume remains constant"

mathematically:

$$\boxed{P \propto T} \quad \left\{ \text{volume is constant} \right\}$$

$$\Rightarrow \frac{P}{T} = c$$

for different sets of conditions

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} = \frac{P_3}{T_3} = c$$

Joule's Law:

→ The change of Internal energy of a perfect gas is directly proportional to the change of Temp.

mathematically

$$\boxed{dU \propto dT}$$

Avogadro's Law:

→ It states that, Equal volumes of all gases, at the same temperature and pressure, contains equal number of molecules.

$$V \propto n \quad \left\{ \begin{array}{l} \text{pressure and Temp.} \\ \text{constant} \end{array} \right.$$

Ideal Gas equation in terms of no. of molecules:

$$P V_s = R T$$

$$\Rightarrow m P V_s = m R T \quad \left\{ \begin{array}{l} \text{multiplying mass (m) both sides} \end{array} \right.$$

$$\Rightarrow P V = m R T$$

we know,

$$\text{mass (m)} = \text{no. of molecules (n)} \times \text{molecular mass of each molecule (M)}$$

$$\Rightarrow m = n \times M$$

$$\text{So } P V = n \times M \times R T$$

$$\Rightarrow \boxed{P V = n R_u T} \quad (\because R_u = M R)$$

Universal Gas constant or Molar constant (R_u)

→ The universal gas constant or molar constant (denoted by R_u or $\bar{R}$) of a gas is the product of the ^{characteristic} gas constant and the molecular mass of the ~~gas~~ gas.

So,

$$\boxed{R_u = MR}$$

where,

$R_u \rightarrow$ universal gas constant

$M \rightarrow$ molecular mass of the gas (kg-mole)

$R \rightarrow$ Characteristic Gas constant

Notes:

① The value of R_u is same for all gases

② In S.I units, the value of R_u is taken

as 8314 J/kg-mol-K or $8.314 \text{ kJ/kg-mol-K}$

③ The characteristic gas equation

$\boxed{PV = RT}$ can be expressed in terms

of molecular mass $\boxed{PV = MRT}$, when

there is $MR = R_u$, so $\boxed{PV = R_u T}$

(condition the gas contains a single no. of molecule)
i.e. $n=1$

④ The characteristic gas equation may also be described by (for n number of molecules having M kg-mole of molecular mass)

$$PV = MRT$$

$$\Rightarrow PV = n \cdot MRT$$

$$\Rightarrow \boxed{PV = n \cdot R_u T} \text{ or simply } \boxed{PV = nRT}$$

(Note: In $PV = nRT$, R is universal gas constant)

$$R_u = 8314 \text{ J/kg-mol-K or } 8.314 \text{ kJ/kg-mol-K}$$

Specific heats of a Gas :

- The specific heat of a substance may be broadly defined as the amount of heat required to raise the temperature of its unit mass through one degree.
- All the liquids and solids have one specific heat only. But a gas can have any number of specific heats (lying between zero & infinity) depending upon the conditions, under which it is heated.
- From the subject point of view the following two types of specific heats are important;

① specific heat at constant volume (C_v)

② specific heat at constant pressure (C_p)

① specific heat at constant volume (C_v) :

→ It is the amount of heat required to raise the temp. of a unit mass of gas through one degree when it is heated at a constant volume.

→ It is generally denoted by C_v

② specific heat at constant pressure (C_p) :

→ It is the amount of heat required to raise the temperature of a unit mass of a gas through one degree, when it is heated at constant pressure.

→ It is generally denoted by C_p .

Regnault's Law:

→ This law states "The two specific heats of a gas (i.e. the specific heat at constant pressure and specific heat at constant volume) do not change with the change in pressure and temp. of the gas."

Relationship between C_p and C_v :

$$\textcircled{1} \quad C_p - C_v = R$$

} $R \rightarrow$ Characteristic gas constant
 $R = 287 \text{ J/kg}\cdot\text{K}$ or $0.287 \text{ kJ/kg}\cdot\text{K}$

$$\textcircled{2} \quad \frac{C_p}{C_v} = \gamma$$

$$C_p - C_v = R$$

$$\Rightarrow \frac{C_p}{C_v} - \frac{C_v}{C_v} = \frac{R}{C_v}$$

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

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

or

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

Q. Derive the relationship between C_p , C_v and R .

we know that,

$$Q \propto M$$

and $Q \propto \Delta T$

$\left. \begin{array}{l} m \rightarrow \text{mass} \\ \Delta T \rightarrow \text{Change in temp or} \\ \text{temp. difference} \end{array} \right\}$

So, $\underline{Q \propto M \Delta T}$ or $\underline{Q = MC \Delta T}$ (To remove proportionality constant it is multiplied)

① Consider a gas enclosed in a container and being heated, at a constant volume, from the Initial state - 1 to final state - 2.

$$\text{So, } Q_{1-2} = m C_v (T_2 - T_1) \quad \left. \begin{array}{l} \text{For constant volume} \\ \text{heat addition} \end{array} \right\}$$

According to 1st law of thermodynamics, a part of heat is utilised in doing the external work, and the rest remains within the gas, and which is used in increasing the Internal energy of the gas.

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

$$\Rightarrow Q_{1-2} = dU + P(V_2 - V_1) \quad \left. \begin{array}{l} \because W = P \Delta V \end{array} \right\}$$

$$\Rightarrow m C_v (T_2 - T_1) = dU + 0 \quad \left. \begin{array}{l} \because V_2 - V_1 = 0 \text{ (constant volume)} \end{array} \right\}$$

$$\Rightarrow \boxed{dU = m C_v (T_2 - T_1)} \quad \left. \begin{array}{l} \text{For constant volume heat} \\ \text{addition,} \end{array} \right\}$$

Note: At constant volume heat addition, the work done is equal to ~~zero~~ zero or there is no work done & change in Internal energy is equal to heat supplied.

② Again consider the same gas is enclosed in a container and being heated at constant pressure, from the Initial state - 1 to final state - 2.

$$Q_{1-2} = m C_p (T_2 - T_1) \quad \left. \begin{array}{l} \text{For constant pressure} \\ \text{heat addition} \end{array} \right\}$$

Applying 1st law of thermodynamics:

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

$$\Rightarrow mC_p(T_2 - T_1) = mC_v(T_2 - T_1) + P(V_2 - V_1) \quad \left\{ \begin{array}{l} \text{Consider} \\ \text{Initial state} \\ \text{of the gas} \end{array} \right.$$

$$\Rightarrow mC_p(T_2 - T_1) = mC_v(T_2 - T_1) + (P_2 V_2 - P_1 V_1)$$

$$\Rightarrow mC_p(T_2 - T_1) = mC_v(T_2 - T_1) + (mRT_2 - mRT_1) \quad (\because PV = mRT)$$

$$\Rightarrow mC_p(T_2 - T_1) = mC_v(T_2 - T_1) + mR(T_2 - T_1)$$

$$\Rightarrow m \cdot \cancel{(T_2 - T_1)} \cdot C_p = m \cdot \cancel{(T_2 - T_1)} \{ C_v + R \}$$

$$\Rightarrow C_p = C_v + R$$

$$\Rightarrow \boxed{C_p - C_v = R}$$

proved or derived

Note:

When the gas is heated from the initial state-1 to final state-2, at constant pressure heating process, At the initial state-1, the volume of the gas remains constant. So considering at the initial state the value of change in Internal energy will be same as that of the change in Internal energy at constant volume heating process.

$$\underline{dU = mC_v(T_2 - T_1)}$$

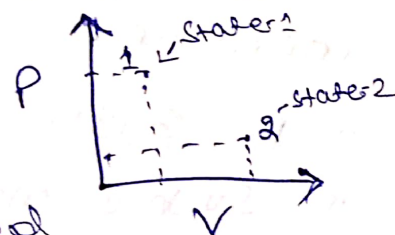
$\left\{ \begin{array}{l} \text{At the initial state of} \\ \text{the gas, when this gas} \\ \text{is heated at constant} \\ \text{pressure} \end{array} \right\}$

Thermodynamic state or state of a system:

→ The state of a system (when the system is in thermodynamic equilibrium) is the condition of the system at any particular moment, which can be identified by the statement of its properties; such as pressure, volume, temperature etc.

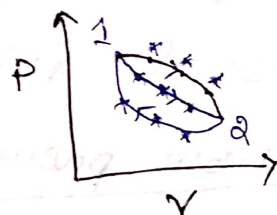
→ Therefore the thermodynamic properties, pressure, temp, volume, density etc. are the state functions or point functions.

* Change of state
An operation in which properties of the system changes is called a change of state.



Thermodynamic Path:

→ During the change of state (From the initial state to the final state), the system passes through the continuous series of equilibrium states. These continuous series of equilibrium states constitutes the path.



Thermodynamic process:

→ When the system changes its state from one equilibrium state to another equilibrium state, then the path of successive states through which the system has passed is known as thermodynamic process.

→ A complete specification of path is referred to as a process.

- * There are two types of Thermodynamic processes.
- ① Quasi-static or Quasi-equilibrium process.
 - ② Non-Quasi Static process.

① Quasi-static process:

→ The ~~term~~ Quasi means almost and static means rest, so Quasi-static process is carried out almost at rest condition i.e. the process is carried out in a very slow manner with a ^{very} ^{very} small difference of pressure.

→ A Quasi-equilibrium process is carried out in such a way that at every instant, the system deviation from the thermodynamic equilibrium is infinitesimal, and in this process each state may be considered as an equilibrium state.

→ For a process to be reversible, it must be Quasi-static i.e. All reversible process is Quasi-static but all Quasi-static process, "consist of friction" is not a reversible process.

Reversible process:

→ In Thermodynamics a reversible process is defined as, a process in which the system and surroundings can be returned to the original state/conditions from the final state without producing any changes/effects in the thermodynamics properties of the universe, if the process is reversed.

* practically no such reversible process exist.

⑧ Non-Quasi-static / Non-equilibrium process:

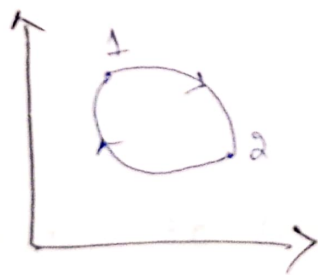
→ In non-quasi-static process the intermediate thermodynamic states (between initial & final state) are not in equilibrium states.

→ Due to have no presence of any equilibrium state it is also referred as non-equilibrium states / process.

Thermodynamic cycle:

→ Thermodynamic cycle is a sequence of thermodynamic processes that begins and ends at the same state.

→ When a system in a given state undergoes through a series of processes such that the final state is identical with the initial state, a cyclic process or a cycle is said to have been executed.



2014/15 New

Q. An Ideal gas 0.9 kg having gas constant $287 \text{ J/kg}\cdot\text{K}$ is heated at constant pressure of 8 bar from 30°C to 200°C . If the specific heat at constant volume is $0.72 \text{ kJ/kg}\cdot\text{K}$.

Find:

- (i) specific heat at constant pressure (c_p)
- (ii) Total heat supplied to the gas (Q)
- (iii) Increase in Internal energy
- (iv) work done in expansion.

given data

$$m = 0.9 \text{ kg}$$

$$R = 287 \text{ J/kg}\cdot\text{K} = 0.287 \text{ kJ/kg}\cdot\text{K}$$

$$P_1 = 8 \text{ bar} = 8 \times 10^5 \text{ Pascal} = 8 \times 10^5 \text{ N/m}^2$$

$$T_1 = 30^\circ\text{C} = 30 + 273 = 303 \text{ K}$$

$$T_2 = 200^\circ\text{C} = 200 + 273 = 473 \text{ K}$$

$$C_v = 0.72 \text{ kJ/kg}\cdot\text{K}$$

Soln

(i) we know,

$$c_p - c_v = R$$

$$2) c_p = R + c_v = 0.287 + 0.72$$

$$\Rightarrow \boxed{c_p = 1.007 \text{ kJ/kg}\cdot\text{K}}$$

(ii) Initially the gas is heated at constant pressure, so total heat supplied to the gas (at constant pressure)

$$Q = m c_p \Delta T$$

$$\Rightarrow Q = 0.9 \times 1.007 \times (473 - 303)$$

$$\Rightarrow \boxed{Q = 154.071 \text{ kJ}} \quad (\text{Heat supplied at constant pressure})$$

(iii) After constant pressure heating, finally the gas is heated at constant volume, so heat is supplied at constant volume:

$$Q = m c_v \Delta T$$

$$2) Q = 0.9 \times 0.72 \times (473 - 303)$$

$$\Rightarrow \boxed{Q = 110.16 \text{ kJ}} \quad (\text{Heat supplied at constant volume})$$

Again at constant volume heating, the net heat is equal to the change in internal energy, because at constant volume heating work done is 0 (change in volume = 0)

According to 1st law,

$$Q = \Delta U + W$$

$$\Rightarrow Q = \Delta U \quad (\because W = 0, \text{ at constant volume heating})$$

$$\Rightarrow \boxed{\Delta U = 110.16 \text{ KJ}} \quad (\text{Increase in Internal Energy})$$

(iv) work done during expansion:

Note: At the initial stage, when the gas is just started to expand, the volume of gas remains constant, so the change in internal energy of the gas remains same as that of constant volume process.

So,

$$\rightarrow Q = \Delta U + W$$

Heat added at constant pressure

$$\Rightarrow W = Q - \Delta U$$

$$\Rightarrow W = 154.071 - 110.16$$

$$\Rightarrow \boxed{W = 43.911 \text{ KJ}} \quad \leftarrow \text{work done during expansion}$$

Answer

2015 (W) Q. The initial pressure and temperature of certain quantity of air contained in a closed vessel are 15 bar and 30°C respectively. Air is heated until its temperature rises to 100°C . Determine the final pressure.

Given data

$$P_1 = 15 \text{ bar} = 15 \times 10^5 \text{ N/m}^2$$

$$T_1 = 30^\circ\text{C} = 30 + 273 = 303 \text{ K}$$

$$T_2 = 100^\circ\text{C} = 100 + 273 = 373 \text{ K}$$

Solⁿ

Given that, the air is contained in a closed vessel, so the volume remains constant.

According to Gay-Lussac law,

$$P \propto T \text{ (at constant volume)}$$

$$\Rightarrow \frac{P}{T} = C$$

$$2) \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$\begin{aligned} 2) P_2 &= \frac{P_1 \times T_2}{T_1} \\ &= \frac{15 \times 10^5 \times 373}{303} \\ &= 1846534 \text{ N/m}^2 \end{aligned}$$

$$\therefore P_2 = 18.46 \text{ bar}$$

Ans

2014 (W)
(new) Q.

An ideal gas 0.9 kg having gas constant $287 \text{ J/kg}\cdot\text{K}$ is heated at constant pressure of 2 bar from 30° to 200°C . If the specific heat at constant volume is $0.72 \text{ kJ/kg}\cdot\text{K}$. Find:

- (i) Specific heat at constant pressure
- (ii) Total heat supplied to the gas.
- (iii) Increase in internal energy
- (iv) Work done in expansion.

2017 (C) New

Q A perfect gas at pressure 750 kPa and 600°C is expanded to 2 bar pressure, determine final temp. of gas if initial and final volume of gas are 0.2 m³ and 0.5 m³ respectively

given data

$$P_1 = 750 \text{ kPa} = 750 \times 10^3 \text{ N/m}^2$$

$$T_1 = 600^\circ\text{C} = 600 + 273 = 873 \text{ K}$$

$$P_2 = 2 \text{ bar} = 2 \times 10^5 \text{ N/m}^2$$

$$V_1 = 0.2 \text{ m}^3$$

$$V_2 = 0.5 \text{ m}^3$$

$$T_2 = ?$$

solⁿ For perfect gas, General gas equation is

$$\frac{PV}{T} = C$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\Rightarrow T_2 = \frac{P_2 V_2 \cdot T_1}{P_1 V_1}$$

$$2) T_2 = \frac{2 \times 10^5 \times 0.5 \times 873}{750 \times 10^3 \times 0.2}$$

$$2) T_2 = 582 \text{ K}$$

$$\therefore T_2 = 582 - 273 = 309^\circ\text{C}$$

2017 (W) New

Q one kg. of Ideal gas is heated from 18.3°C to 93.4°C. Assuming $R = 287 \text{ J/kg}\cdot\text{K}$ and $\gamma = 1.18$, for the gas. Find:

(i) specific heats

(ii) change of Internal energy

(iii) change in enthalpy

given data

$$m = 1 \text{ kg}$$

$$T_1 = 18.3^\circ\text{C} = 18.3 + 273 = 291.3 \text{ K}$$

$$T_2 = 93.4^\circ\text{C} = 93.4 + 273 = 366.4 \text{ K}$$

$$R = 287 \text{ J/kg}\cdot\text{K} = 0.287 \text{ kJ/kg}\cdot\text{K}$$

$$\gamma = 1.18$$

Solⁿ

we know,

$$\frac{C_p}{C_v} = \gamma$$

$$1) \frac{C_p}{C_v} = 1.18$$

$$2) C_p = 1.18 C_v$$

again,

$$C_p - C_v = R$$

$$1) 1.18 C_v - C_v = 0.287$$

$$2) 0.18 C_v = 0.287$$

$$3) \underline{C_v = 1.595 \text{ kJ/kg}\cdot\text{K}}$$

$$C_p = 1.87 \text{ kJ/kg}\cdot\text{K}$$

$$1) C_p = 0.287 + 1.595$$

$$2) \underline{C_p = 1.882 \text{ kJ/kg}\cdot\text{K}}$$

ii) change in Internal energy:

$$\Delta U = m C_v \Delta T \quad \left. \begin{array}{l} \text{Initially the volume is constant} \\ Q = \Delta U + W \Rightarrow Q = \Delta U \quad (\because W = 0) \end{array} \right\}$$

$$= 1 \times 1.595 \times (366.4 - 291.3)$$

$$= 119.78 \text{ kJ}$$

iii) change in Entropy:

$$\Delta H = m C_p \Delta T$$

$$= m C_p (T_2 - T_1)$$

$$= 1 \times 1.882 (366.4 - 291.3)$$

$$= 141.26 \text{ kJ}$$

Any

2016/2/11

Q. A vessel of capacity 0.105 m^3 contains gas at a pressure of 0.15 mpa and a temp. of 20°C . Additional gas is now pumped into the system until the pressure rises to 0.75 mpa and temp. rises to 25°C . Determine the mass of gas pumped in and determine the quantity as a volume at a pressure of 0.102 mpa and a temp. of 20°C .

given data

$$V_1 = 0.105 \text{ m}^3$$

$$P_1 = 0.15 \text{ mpa} = 0.15 \times 10^6 \text{ N/m}^2$$

$$T_1 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$$

$$P_2 = 0.75 \text{ mpa} = 0.75 \times 10^6 \text{ N/m}^2$$

$$T_2 = 25^\circ\text{C} = 25 + 273 = 298 \text{ K}$$

$$P_3 = 0.102 \text{ mpa} = 0.102 \times 10^6 \text{ N/m}^2$$

$$T_3 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$$

Soln

Assuming the gas is a perfect gas.

So according to perfect gas equation, for State-1

$$P_1 V_1 = m_1 R T_1$$

$$\Rightarrow m_1 = \frac{P_1 V_1}{R T_1}$$

$$= \frac{0.15 \times 10^6 \times 0.105}{287 \times 293}$$

$$= 0.12729 \text{ kg}$$

Similarly for State-2

$$P_2 V_2 = m_2 R T_2$$

$$\Rightarrow m_2 = \frac{P_2 V_2}{R T_2} = \frac{0.75 \times 10^6 \times 0.105}{287 \times 298}$$

Enthalpy:

→ In thermodynamics, Enthalpy of a gas may be defined as the Total heat content of the system.

→ In other words Enthalpy also describes as the sum of the Internal energy (U) and the product of pressure (P) and volume (V). It is an Extensive property.

→ It is denoted by ' H '

mathematically,

$$H = U + PV$$

where,

$H \rightarrow$ Enthalpy

$U \rightarrow$ Internal Energy

$P \rightarrow$ pressure

$V \rightarrow$ volume.

* For a unit mass, specific enthalpy

$$h = U + PV_s$$

* We cannot calculate the absolute values of Both Internal energy and Enthalpy, but we can calculate the change in Internal energy as well as change in Enthalpy.

Change in Enthalpy:

→ The change in Enthalpy is described as the heat exchanged by the system at constant pressure process.

→ It is denoted by the symbol " ΔH "

→ If the heat is supplied at constant pressure from state-1 to state-2, then the change in Enthalpy:

$$\boxed{\Delta H = H_2 - H_1}$$

→ previously, we know that the heat supplied (Q) at constant pressure

$$\boxed{Q = m C_p \Delta T}$$

* Thus for a constant pressure process, the heat supplied to the gas is equal to the change of enthalpy.

$$\boxed{Q = \Delta H = m C_p \Delta T}$$

constant pressure

(C.P → constant pressure)

$$\text{or } \boxed{Q = \Delta H = H_2 - H_1}$$

C.P

proof

$$Q = \Delta U + W$$

$$\Rightarrow Q = \Delta U + P \Delta V$$

$$\Rightarrow Q = U_2 - U_1 + P(V_2 - V_1)$$

$$\Rightarrow Q = U_2 - U_1 + PV_2 - PV_1$$

$$\Rightarrow Q = U_2 + PV_2 - U_1 - PV_1$$

$$\Rightarrow Q = U_2 + PV_2 - (U_1 + PV_1)$$

$$\Rightarrow \boxed{Q = H_2 - H_1}$$