Thermodynamics:

Can be defined as the science of energy. The name thermodynamics stems from the Greek words thermos (heat) and dynamics (power).

Applied thermodynamics: is the science of relationship between heat, work, and the properties of the system. It is concerned with the means necessary to convert heat energy from available sources such as chemical fuels or nuclear piles into mechanical work.

Working substance:

The working substances are in general fluids which are capable of deformation in that they can readily be expanded and compressed. Common examples of working substance used in thermodynamic system air and steam.

Pure substance:

Is a single substance or mixture of substance which has the same consistent composition throughout. Such as water, nitrogen, helium, and carbon dioxide. In other words, it is a homogenous substance and its molecular structure does not vary.

For example, steam or water or mixture of both can be considered as a pure substance. This is because it has the same molecular or chemical structure through its mass.

Dimensions and units:

Any physical quantity can be characterized by "dimensions" the arbitrary magnitudes assigned to the dimensions are called "units".

Some basic dimensions such as mass (m), length (L), time (t), and temperature (t), are selected as [primary] or fundamental dimensions, while others such as velocity (v), energy (E), and volume (V) are expressed in terms of the primary dimensions and are called [secondary] dimensions, or derived dimensions.

Two sets of units are still in common use today:

1- **The English System** 2- **System International (SI) unit**

Dimension	***Unit***
Length	Meter (m)
Mass	Kilogram (kg)
Time	Second (s)
Temperature	Kelvin (k)
Electric current	Ampere (A)
Amount of light	Candela (c)
Amount of matter	Mole (mol)

quantity	**SI Units**	**From English to SI Units**
Area	m^2	1 ft = 0.3048 m
Density	kg/m^3	1 in = 0.0254 m
Energy	J	1 ibm = 0.4536 kg
Energy per unit mass	J/kg	1 slug = 14.594 kg
Force	N	1 ib_f = 4.448 N
Heat flux	W/m^2	
Heat transfer rate	W	1Btu = 1055.06 J 1cal = 4.1868 J 1 Btu/Ibm = 2326 J/kg
Mass flow rate	Kg/s	
Power	W (J/s)	1 hp = 745.7 w
Pressure and stress	N/m^2	1 Ib_f /ft^2 = 47.88 N/m^2

Specific heat	J/kg.k	1 psi = 1 Ib_f /in^2 = 6894.8 N/m^2
Surface tension	N/m	
Velocity	m/s	1 standard atmosphere = 1.0133*10^5 N/m^2
Viscosity (kin.)	m^2/s	
Volume	m^3	1 gal = 0.003785 m^3
Volume flow rate	m^3/s	
Specific volume	m^3/kg	

Heat Engine:

Is the name given to a system which by operating in a cyclic manner produces network from a supply of heat.

Heat, Work, and the System:

Heat is a form of energy which is transferred from one body to another body at a lower temperature by virtue of the temperature difference between the bodies.

Note that the heat and work are transient quantities, not properties.

In mechanics, **work** is defined as the product of the force (F) and the distance moved (x) in the direction of the force → $W = F * x$

If a system exists in which a force at the boundary of the system is moved through a distance, then work is done by or on the system.

Work = Force * distance ……..*

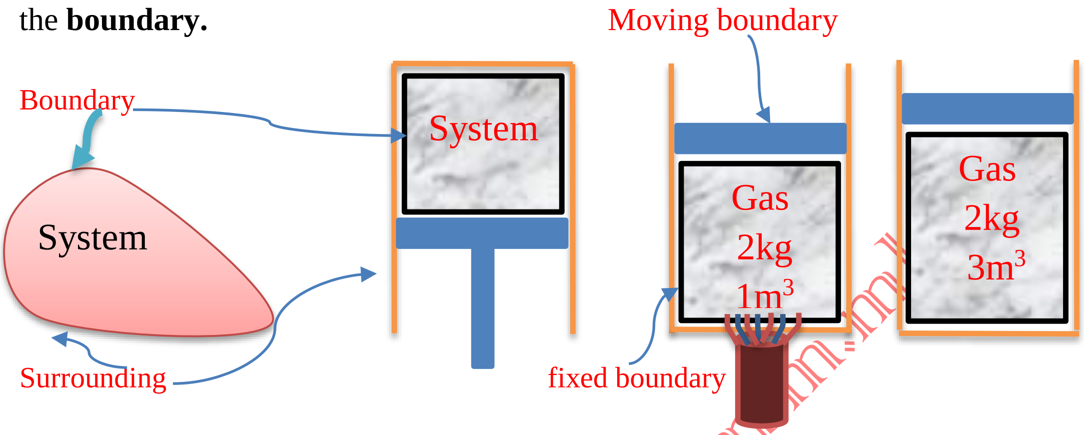
A **system** may be defined as a collection of matter within prescribed and identifiable boundaries.

Or:

A quantity of matter or a region in space chosen for study.

The mass or region outside the system is called **Surrounding**.

The real or imaginary surface that separates the system from its surrounding is called the **boundary.**

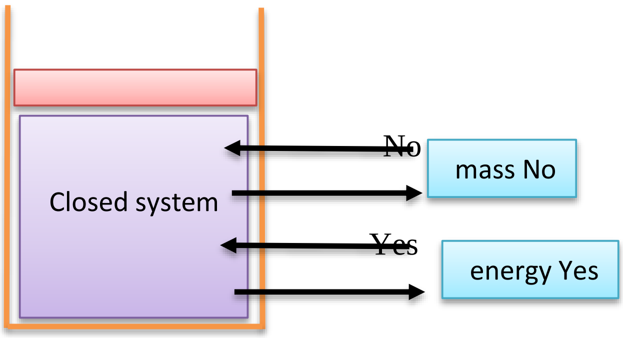


Closed and Open System:

System may be considered to be closed or open depending on whether a fixed mass or a fixed volume in space is closen for study.

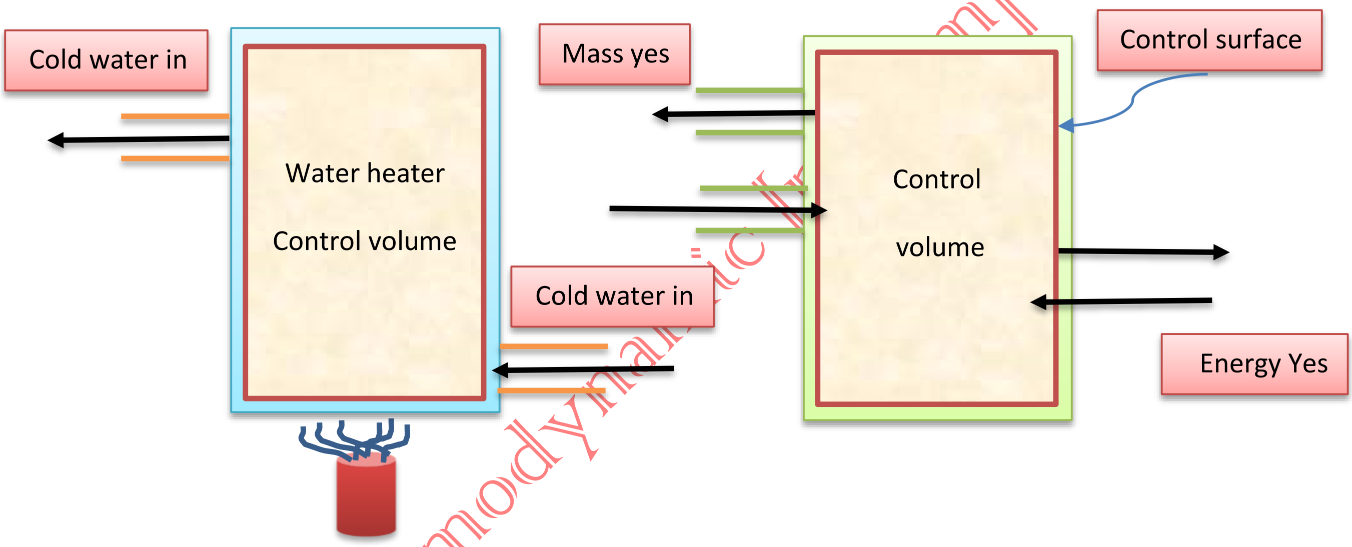
A closed system (also known as a control mass) consists of a fixed amount of mass, and no mass can cross its boundary. That is, no mass can enter or leave a closed system.

But energy in the form of heat or work, can cross the boundary, and the volume of a closed system does not have to be fixed.



If, as special case, even energy is not allowed to cross the boundary, that system is called an **isolated system**.

An Open System, or a control volume, as it is often called, is a properly selected region in space. It usually encloses a device that involves mass flow, such as a compressor, turbine, or nozzle. Both mass and energy can cross the boundary of a control volume which is called **a control surface**.



[An open system (a control volume)
with one inlet and one exit]

[both mass and energy can cross
the boundaries of a control volume]

Properties of a System:

Any characteristic of a system is called a property. Some familiar examples are pressure **P**, temperature **T**, volume **V**, and mass **m**.

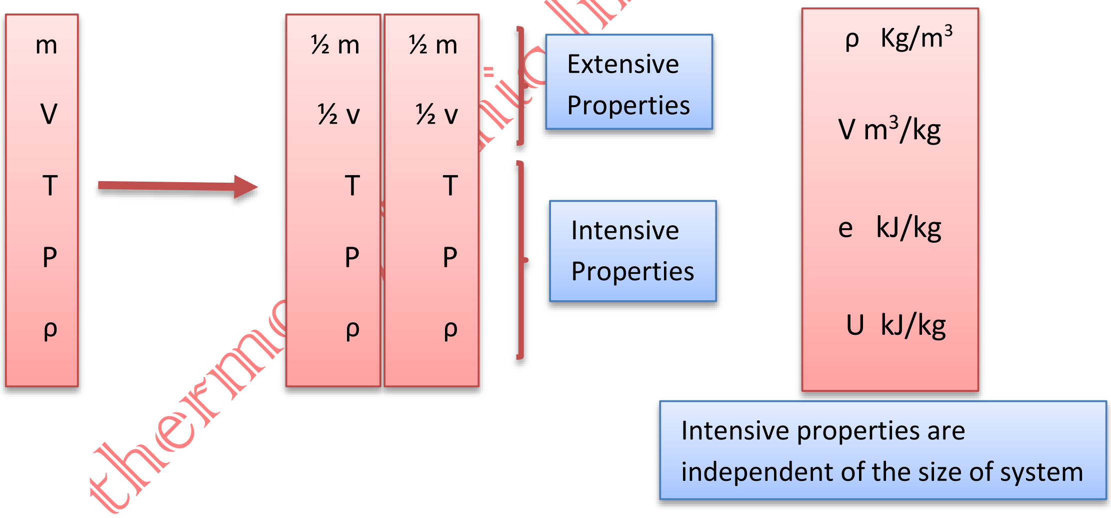
The list can be extended to include less familiar ones such as viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity, and even velocity and elevation.

Not all properties are independent; some are defined in terms of other ones, such as density (ρ), specific volume (υ), specific gravity (ρ_s).

Properties are considered to be either **intensive** or **extensive**.

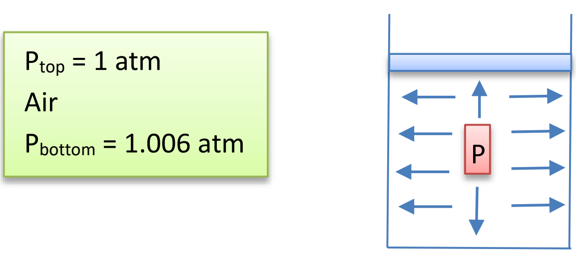
Intensive properties are those that are independent of the size of a system, such as temperature, pressure, and density.

Extensive properties are those whose values depend on the size -or extent- of the system, such as mass, volume, and total energy (E).



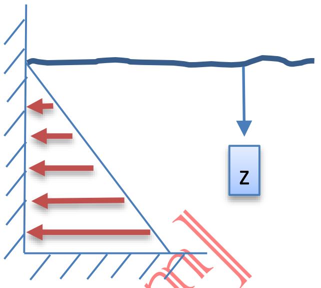
Pressure:

Is the force exerted by a fluid per unit area. We speak of pressure only when we deal with a gas or a liquid. The counterpart of pressure in solids is stress.



In a container filled with a gas

the variation of pressure with height is negligible



The pressure of a fluid at rest increases

with depth (as a result of added weight)

Since pressure is defined as force per unit area, it has the unit of newtons per square meter (N/m^2), which is called a **pascal (pa)**.

P = F / A ……..*

1 N = 1 kg . m / s^2

1 pa = 1 N/ m^2

1 Mpa = 10^6 pa

1 kpa = 10^3 pa

Two other common pressure units are **bar** and **standard atmosphere**:

1 bar = 10^5 pa = 0.1 Mpa = 100 kpa

1 atm = 101325 pa = 101.325 kpa = 1.01325 bars

In the English system, the pressure unit is [pound- force per square inch]

Ib_f / in^2 or psi

1 atm = 14.696 psi = 760 mm Hg

The actual pressure at a given position is called **the absolute pressure**, and it is measured relative to absolute vacuum, i.e., absolute zero pressure.

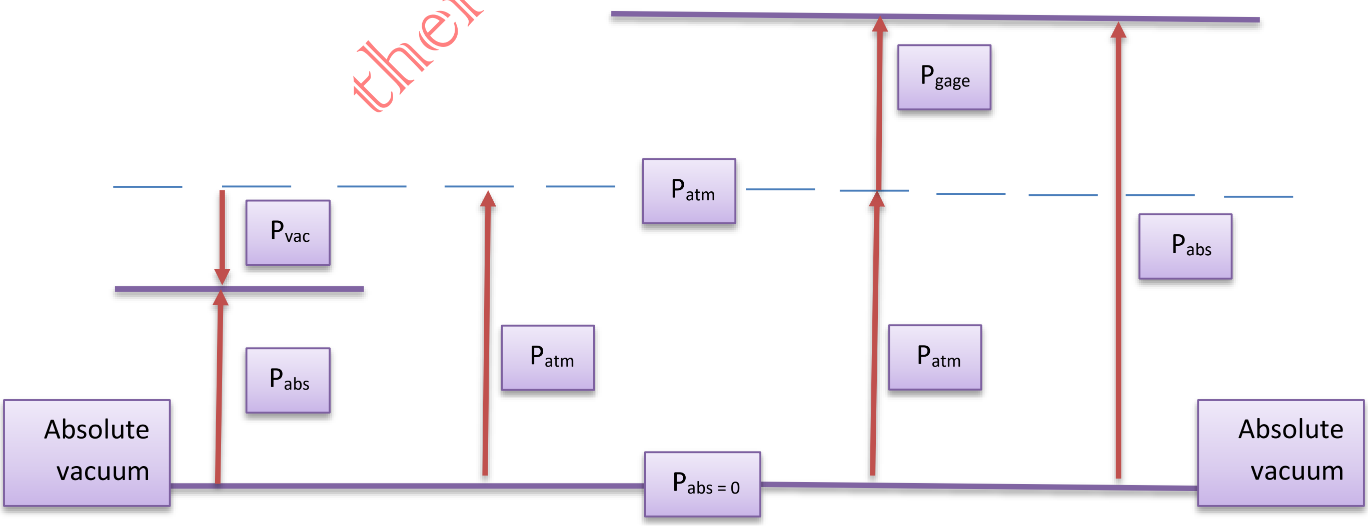
The difference between the absolute pressure and the local atmospheric pressure is called the **gage pressure**.

Pressures below atmospheric pressure are called **vacuum pressure**, and are measured by vacuum gage.

Absolute, gage, and vacuum pressure are all positive quantities and are related to each other by:

$P_{gage} = P_{abs.} - P_{atm.}$ [For pressure above $P_{atm.}$]

$P_{vac.} = P_{atm.} - P_{abs.}$ [For pressure below $P_{atm.}$]



Ex1: A vacuum gage connected to a chamber reads 5.8 psi at a location where the atmospheric pressure is 14.5 psi. Determine the absolute pressure in the chamber.

Sol:

$P_{abs.} = P_{atm.} - P_{vac.}$

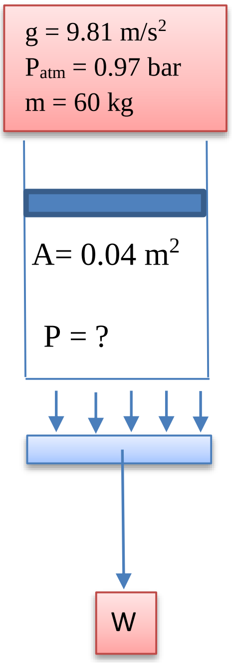
$= 14.5 - 5.8$

$= 8.7$ psi

Ex2: The piston of a piston-cylinder device containing a gas has a mass of 60 kg and a cross-sectional area of 0.04m^2, as shown below. The local atmospheric pressure is 0.97 bar and the gravitational acceleration is 9.8 m/s^2.

a. Determine the pressure inside the cylinder.

b. If some heat is transferred to the gas and its volume doubles, do you expect the pressure inside the cylinder to change?



Sol:

a. Equilibrium → $\sum F = 0$

$p.A = P_{atm.}\,A + W$, $W = mg$

$P = P_{atm.} + mg/A$

$$= 0.97 \text{ bar} + \frac{60\,kg * 9.8\frac{m}{s^2}}{0.04\,m^2} * \frac{1N}{1\,kg\,.\frac{m^2}{s^2}} * \frac{1bar}{10^5\ \frac{N}{m^2}}$$

= 1.117 bars

Temperature:

Although we are familiar with temperature as a measure of "hotness" or "coldness" it is not easy to give an exact definition for it.

Based on our physiological sensations, we express the level of temperature qualitatively with words like freezing cold, cold, warm, hot, and red- hot.

The variation of an easily measurable property of a substance with temperature can be used to provide a temperature- measuring instrument. For example, the length of a column of mercury will vary with temperature due to the expansion and contraction of the mercury or another liquid, gas, and solid.

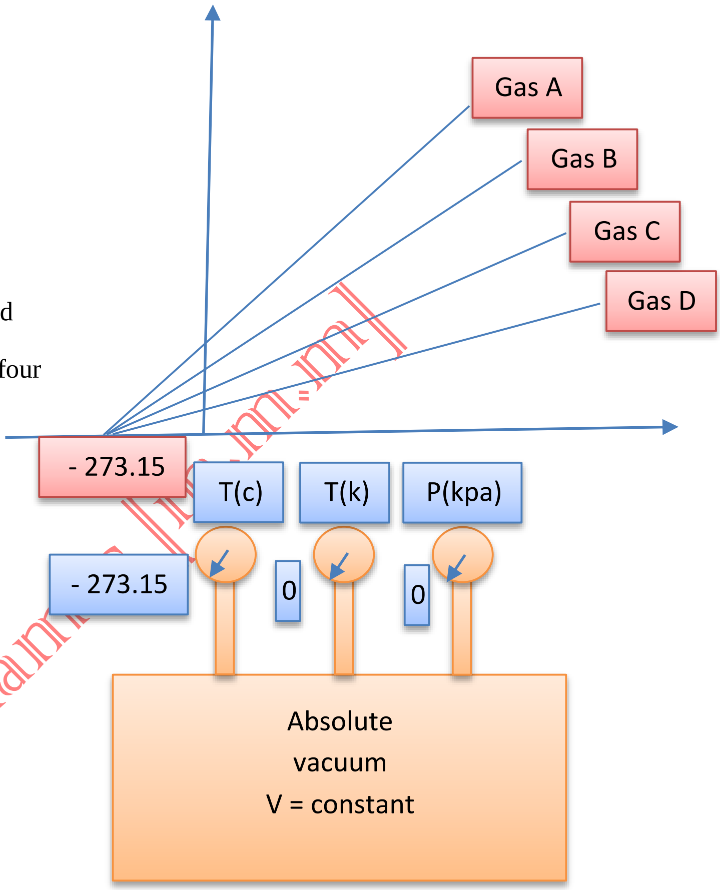
Temperature scales:

The temperature scales used in the SI and in the English system today are the Celsius Scale (formerly called the Centigrade scale) and the Fahrenheit Scale.

On the Celsius scale, the ice and steam point, are assigned the values of 0 and $100C^{\circ}$, respectively, the corresponding values on the Fahrenheit scale are 32 and $212F^{\circ}$.

In thermodynamics, it is very desirable to have a temperature scale that is independent of the properties of any substance or substances. The thermodynamic temperature scale in the SI is the Kelvin scale. The temperature unit on this scale is the kelvin, which is designated by **K**(not $^{\circ}$**K**).the lowest temperature on the kelvin scale is ,0,K.

The thermodynamic temperature scale in the English system is the **Rankine scale**; the temperature unit on this scale is the Rankine, which is designated by **R**.



[P versus T plots at the experimental data obtained from a constant- volume gas thermometer using four different gases at different pressure].

$T(k) = T(°C) + 273.15$ …………*

$T(R) = T(°F) + 459.67$ ………….*

$T(R) = 1.8\ T(K)$ ………..*

$T(°F) = 1.8\ T(°C) + 32$ …………*

$\Delta T\ (R) = 1.8\ \Delta T(K)$

$\Delta T\ (K) = \Delta T\ (°C)$ …………*

$\Delta T\ (R) = \Delta T\ (°F)$ …………*

A constant volume gas thermometer would read -273.15 at absolute zero pressure

Ex3: During a heating process, the temperature of a system rises by 10°C. Express this rise in temperature in K, °F, and R.

Sol:

$\Delta T\ (K) = \Delta T\ (°C) = 10°C$

$\Delta T\ (R) = 1.8\Delta T\ (K)$

$= 1.8 * 10 = 18\ R$

$\Delta T\ (°F) = \Delta T\ (R) = 18\ °F$

Volume:

Volume is a property, being that property which is associated with cubic measure.

The unit of volume is the cubic meter (m^3), sometimes the liter L may be used.

1 liter = 1 cubic decimeter ($1\ dm^3 = [10^{-1}m]^3$)

If the volume of a substance increases then the substance is said to have been expanded.

If the volume of a substance decreases then then the substance is said to have been compressed.

Specific volume is given the symbol (υ)

$\upsilon = \frac{V}{m}\ \ m^3/kg$

υ: it is the reciprocal of density and is defined as the volume per unit mass.

Density defined as mass per unit volume.

$\rho = \frac{m}{v}$ kg/m3

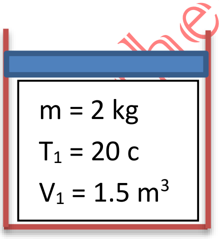
Specific gravity or relative density:

Is defined as the ratio of the density of a substance to the density of some standard substance at specified temperature, [(usually water at 4°C) for which $\rho\ H_2O$ =1000 kg/m3]

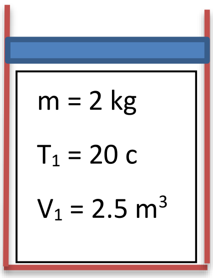
$$\rho s = \frac{\rho}{\rho H_2O}$$

State and Equilibrium:

Consider a system that is not undergoing change. At this point, all properties can be measured or calculated throughout the entire system, which gives as a set of properties that completely describe the condition, or the state of the system.



a- state-1



b- state-2

Thermodynamics deals with equilibrium states. The word equilibrium implies a state of balance. In an equilibrium state, there are no unbalanced potentials (or driving forces) within the system.

Types of Equilibrium:

Thermal equilibrium: if the temperature is the same throughout the entire system, then the system is in thermal equilibrium.

[A closed system reaching thermal equilibrium]

Mechanical Equilibrium: is related to pressure, and a system is in mechanical equilibrium if there is no change in pressure at any point of the system with time.

Phase Equilibrium: if a system involves two phases, it is phase equilibrium when the mass of each phase reaches an equilibrium level and stays there.

Chemical Equilibrium: a system is in chemical equilibrium if its chemical composition does not change with time (no chemical reactions occur).

A system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

Processes and Cycles:

Any change that a system undergoes from one equilibrium state to another is called a process, and the series of states through which a system passes during a process is called the path of the system.

Process diagrams that plotted by employing

thermodynamic properties as coordinates are very useful in visualizing the processes.

Some common properties that are used as coordinates are temperature (T), pressure(P), and volume (V),[or specific volume(υ)].

The prefix iso- is often used to designate a process for which a particular property remains constant.

An isothermal process, for example, is a process during which the temperature (T) remains constant.

An isobaric process is a process during which the pressure P remains constant.

An **isochoric** (or isometric) process is a process during which the specific volume υ remains constant.

A system is said to have undergone a cycle if it returns to its initial state at the end of the process. That is, for a cycle the initial and final states are identical.

Types of thermal cycle:

Thermodynamic cycle: in this cycle no change in the chemical structure and the properties of fluid, for example the steam in power plant.

Mechanical cycle: in this cycle the properties of fluid or substance will be change, for example the internal combustion engine (I.C.E).

Energy:

Energy is defined as that capacity a body or substance processes which can result in the performance of work. From the law of conservation of energy the energy cannot be created or destroyed.

Form of energy: energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **Total Energy** "E" of a system. The total energy of a system on unit mass basis denoted by "e" and is defined as:

$$e = \frac{E}{m} \quad \text{kJ/kg}$$

In thermodynamic analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups:

Microscopic   2- Macroscopic

The microscopic forms of energy are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames.

The sum of all the microscopic forms of energy is called the "Internal Energy" of a system and is denoted by "U".

$U = m \, . \, u$ kJ

m = mass kg

u = specific internal energy kJ/kg

The macroscopic energy of a system is related to motion and the influence of some external effect such as gravity, magnetism, electricity, and surface tension.

The energy that a system processes as a result of its motion relative to some reference fram is called "**Kinetic Energy**" KE.

$$dE = F \, . \, dx$$

$$\int dE = \int F \, . \, dx$$

$$F = m \, . \, a = m \, . \frac{dc}{dt}$$

c = velocity

t = time

$$\int dE = \int m\,.\frac{dc}{dt}.\,dx$$

$$\int dE = m\int \frac{dx}{dt}.\,dc \qquad ,\frac{dx}{dt} = c$$

$$= m\int C\,dc$$

$$\int_0^E dE = m\int_{C1}^{C2} C\,dc$$

$$= m\left[\frac{C^2}{2}\right]$$

$$K.E = \frac{1}{2}m\,(C_2^2 - C_1^2) \quad , C1 = 0 \quad , E = K.E$$

$$K.E = \frac{1}{2}\,m\,C_2^2 \qquad kJ$$

Or, on a unit mass basis (specific kinetic energy)

$$k\,.\,e = \frac{c^2}{2} \qquad kJ/kg$$

Single phase point (Triple point) of water: The state in which the solid, liquid and vapor exist-together.

The energy that a system processes as a result of its elevation in a gravitational field is called Potential Energy "PE" and is expressed as:

PE = W. Z

= m g z Jole (N.m)

Or, on a unit mass basis, (specific potential energy)

$Pe = g\,z$ kJ/kg

g = gravitational acceleration.

z = elevation.

Any volume of fluid entering or leaving a system displace an equal volume, the energy produced due to this flow is called Flow Energy "FE".

F. E = P. V

Heat Energy: it is one form of energy that produced only when temperature difference between the system and surrounding. There are three types of heat transfer:

Conduction 2- Convection 3- Radiation

Heat energy is given the symbol "Q", to indicate a rate of heat transfer a dot is placed over the symbol Q, thus:

Q = heat transfer / unit time

Work Energy: it is a form of energy defined as the multiplication of the force that effected on the mass by the distance that the mass will be moved due to this effect.

$dw = F.\,dL$, $F = P\,.\,A$

$= P.\,A.\,dL$, $dv = A.\,dL$

$= P.\,dv$

$$\int_1^2 dw = \int_{V_1}^{V_2} P.\,dv$$

$$W_{1-2} = \int_{V_1}^{V_2} P.\,dv \qquad \text{kJ}$$

$$W_{1-2} = \int_{V_1}^{V_2} P\,.\,dv \qquad kJ/kg$$

Power: is the rate of doing work.

$$power = \frac{\text{Work done}}{\text{Time taken}} \quad , \frac{\text{Joule}}{\text{second}}$$

$$P = \frac{W}{t} \qquad J/s = watt$$

Power = w. m• $\qquad \frac{KJ}{Kg}.\frac{Kg}{S} = \frac{KJ}{S} = kw$

m• = flow rate = ρ C A

ρ: density (kg/m3) ,C: velocity (m/s) ,A: Area(m2)

Spring Work:

dw = F . dx ………(1)

F = k . x ………(2)

k= Spring constant (kN/m)

sub equ. (2) in (1)

$$\int dw = \int_{x_1}^{x_2} k.\,x.\,dx$$

Wspring = $\frac{1}{2}k(x_2^2\_x_1^2)$

Ex4: An insulated (2kg) box falls from a ballon (3.5km) above the earth. What's the change in potential energy of the box?

Ex5: A force (F) is proportional to (x^2) and has the value of (133N) when (x=2), Determine the work done by it moves in object from (x=1) to (x=4) where (x) in meter.

Ex6: Let the pressure in the cylinder in the figure given by the equation ($P = \frac{c}{V}$) as function of volume.

Find the work done, if the initial pressure is (400 kpa), the initial volume (0.02 m3) and the final volume is (0.08 m3).

Is the sign correct?

Ex7: The pressure in the cylinder shown below varies in the following manner with volume $= \frac{c}{V^2}$, if the initial pressure (500 kpa), initial volume is (0.05 m3), and the final pressure is (200 kpa). Find the work done by the system?

Ex8: A fluid in a cylinder is at a pressure of (700 kN/m2).it is expanded at constant pressure from a volume of (0.28 m3) to a volume of (1.68 m3). Determine the work done.

Reversibility:

A more rigorous definition of reversibility is as follows: when a fluid undergoes a reversible process, both the fluid and its surroundings can always be restored to their original state. The criteria of reversibility are as follows:

1. The process must be frictionless.
2. The difference in pressure between the fluid and its surroundings during the process must be infinitely small.
3. The difference in temperature between the fluid and its surroundings during the process must be infinitely small.

A reversible process between two states drawn as a line on any diagram of properties.

An irreversible process is usually represented by a dotted line joining the end states to indicate that the intermediate states are indeterminate.

Internal reversibility:

It is may be obtained, because no process in practice is truly reversible, but with conditions below:

1. The surrounding can never be restored to their original state.
2. The fluid itself is at all times in an equilibrium state and the path of the process can be exactly retraced to the initial state.

Reversible work:

Consider an ideal frictionless fluid contained in a cylinder behind a piston, with the following assumptions:

1. The pressure and temperature of the fluid are uniform.
2. No friction between the piston and the cylinder walls.

Work done by fluid = (PA)*dL

$= p \,.\, dv$ per unit mass

Work done = P dυ (where υ is the specific volume)

Work done = shaded area

$$= \int_1^2 p \,.\, dv$$

The zeroth law (law number zero):

This law is concerned with thermal equilibrium.it states that "if two bodies are separately in thermal equilibrium with a third body then they must be in thermal equilibrium with each other.

If $T_A = T_B$

$T_A = T_C$

$\therefore T_B = T_C$ (thermal equilibrium)

The first law of thermodynamics:

The concept of energy and the hypothesis that it can be neither created nor destroyed were developed by scientists in the early part of the nineteenth century and became known as the principle of the conservation of energy. The First Law of Thermodynamics is merely one statement of this general principle with particular reference to heat energy and mechanical energy (work).

The First Law of Thermodynamics can be stated as follows:

"When a system undergoes a thermodynamic cycle then the net heat supplied to the system from its surrounding is equal to the net work done by the system on its surrounding". In symbols,

$Q = q \cdot m$

$W = w \cdot m$

$\sum dQ = \sum dW$ kw

$\sum dq = \sum dw$ kJ/kg

Where $\sum$ represents the sum for a complete cycle.

Ex9: In a certain steam plant the turbine develops 1000 kw, the heat supplied to the steam in the boiler is 2800 kJ/kg, the heat rejected by the system to cooling water in the condenser is 2100 kJ/kg and the feed pump work required to pump the condensate back into the boiler is 5 kw. Calculate the steam flow in kg/s.

-The steady- flow energy equation: (SFEE)

This equation is a mathematical statement of the principle of conservation of energy as applied to the flow of a fluid through a thermodynamic system.

The various forms of energy which the fluid can have are as follows:

a. Potential Energy: $P.E = m.\,g.\,z$ kJ

b. Kinetic Energy: $K.E = \frac{1}{2}.m.C^2$ kJ

c. Internal Energy: $U = m.\,u$ kJ

d. Flow or displacement Energy: $F.E = p.\,v$ kJ

e. Heat received or rejected "Q".

f. External work done "W".

Applying the principle of conservation of energy to the system (or c.v.), then,

Total energy entering the system = Total energy leaving the system

$$E_{input} = E_{output}$$

$$P.\,E_1 + I.\,E1 + F.\,E_1 + K.\,E_1 + Q = P.\,E_2 + I.\,E2 + F.\,E_2 + K.\,E_2 + W$$

For 1kg of fluid mass:

$$gz_1 + u_1 + p_1\upsilon_1 + \frac{1}{2}\,c_1^2 + q = gz_2 + u_2 + p_2\upsilon_2 + \frac{1}{2}\,c_2^2 + w$$

or:

$$gz_1 + (u_1 + p_1\upsilon_1) + \frac{1}{2}\,c_1^2 + q = gz_2 + (u_2 + p_2\upsilon_2) + \frac{1}{2}\,c_2^2 + w$$

"Steady- Flow Energy Equation" SFEE

$$gz_1 + h_1 + \frac{1}{2}\,c_1^2 + q = gz_2 + h_2 + \frac{1}{2}\,c_2^2 + w$$

Where: q & w per unit mass.

Mass flow rate: $= \dot{m} = \frac{C\,A}{\vartheta} = \rho CA,\ \dot{m}_1 = \dot{m}_2$

❖ This equation is known as the continuity of mass equation.

$$m^{\cdot} = \frac{C_1A_1}{\vartheta_1} = \frac{C_2A_2}{\vartheta_2}$$

-The non- flow energy equation: "NFEE"

In the case of a closed system, however, in which the fluid mass remains constant, no substance passing through the system boundary, the flow terms in steady flow E.E will not apply. Thus the terms Pυ and $C^2/2$ are neglected. The system is then said to be non-flow.

From the SFEE:

$$gz_1 + u_1 + p_1\upsilon_1 + \frac{1}{2}\,c_1^2 + q = gz_2 + u_2 + p_2\upsilon_2 + \frac{1}{2}\,c_2^2 + w$$

$$u_1 + q = u_2 + w_1$$

$q - w = u_2 - u_1$ ……..* "NFEE" per 1kg

When, $\Delta Z,\ \Delta C^2 \approx 0$

$q - w = h_2 - h_1$ .... * "SFEE" per 1kg

Some Applications of the SFEE:

1. ***Steam boilers:***

$$gz_1 + h_1 + \frac{1}{2}\,c_1^2 + q = gz_2 + h_2 + \frac{1}{2}\,c_2^2 + w$$

In boiler: a) $w = 0$

b) $\frac{c_2^2 - c_1^2}{2}$ very small

c) $\Delta Z \approx 0$

$\therefore\ q = h_2 - h_1$ kJ/kg

$Q = \dot{m}_s (h_2 - h_1)$ kJ/s (kw)

$\dot{m}_s$ = steam flow rate kg/s

$\dot{m}_s = \rho C A$

2. ***Turbine:***

$$gz_1 + h_1 + \frac{1}{2} c_1^2 + q = gz_2 + h_2 + \frac{1}{2} c_2^2 + w$$

In turbine: a) $Q = 0$

b) $\frac{c_2^2 - c_1^2}{2} \approx 0$

c) $\Delta Z \approx 0$

$\therefore h_1 = h_2 + w \rightarrow w = h_1 - h_2$ kJ/kg

$\dot{w} = \dot{m}_s (h_1 - h_2)$ kJ/s (kw)

3. ***Heat exchanger:***

In heat exchanger: a) $w = 0$

b) $\frac{c_2^2 - c_1^2}{2} \approx 0$ (neglect)

c) $\Delta Z \approx 0$

From SFEE:

$\therefore q = h_2 - h_1$ (rejected heat)

$Q = \dot{m}_s (h_2 - h_1)$

$Q = \dot{m}_s (h_2 - h_1) = \dot{m}_w C_{P\,w} (T_{w\,(out)} - T_{w\,(in)})$

$\dot{m}_s$ = steam flow rate, $\dot{m}_w$ = cooling water flow rate.

$C_{P\,w}$ = specific heat of water at constant pressure.

$T_{w\,(out)}$ = outlet water temperature.

$T_{w\,(in)}$ = inlet water temperature.

4. ***Nozzle:***

In nozzle: a) $Q = 0$

b) $w = 0$

c) $\Delta Z = 0$

From SFEE:

$$\frac{C_2^2}{2} - \frac{C_1^2}{2} = h_1 - h_2$$

When $C_1 \approx 0$

$$\frac{C_2^2}{2} = h_1 - h_2$$

$$\therefore C_2 = \sqrt{2(h_1 - h_2)} \quad \text{m/s}$$

Specific heats:

Is defined as the energy required to raising the temperature of a unit mass of a substance by one degree.

$Q = m.\ C.\ \Delta T$ ………* kJ

C = specific heat capacity kJ/kg.k

m = mass of substance.

Q = heat transferred to produce temperature change.

In general, the energy required to raise the temperature will depend on how the process is executed.

In thermodynamics, we are interested in two kinds of specific heats:

1. Specific heat at constant volume "C_v".
2. Specific heat at constant pressure "C_p".

Physically, the specific heat at constant volume C_v can be viewed as the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

The energy required to do the same as the pressure is maintained constant is the specific heat at constant pressure C_p.

This is illustrated in fig. below. The specific heat at constant pressure C_p is always greater than C_v because at constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system.

$Q = m\ C\ \Delta T$

For unit mass

$q = C\ \Delta T$

$dq = CdT$

$\therefore C \frac{dq}{dT}$ ………*

1. *At constant volume:*

From NFEE:

$q - w = \Delta u$, at $v = c \rightarrow w = 0$

$q = \Delta u \rightarrow dq = du$

$$C_V = \frac{dq}{dT} = \frac{du}{dT} \rightarrow du = C_V dT \rightarrow \Delta u = C_V \Delta T$$

∴ at constant volume $Q = \Delta u = m\, C_v\, \Delta T$ ....*

2. *At constant pressure:*

$W = P_2V_2 - P_1V_1$

$q = w + \Delta u$

$q = (p_2v_2 - p_1v_1) - (u_2 - u_1)$

$q = (p_2v_2 + u_2) - (p_1v_1 + u_1)$

$q = h_2 - h_1$

$q = \Delta h$

$dq = dh$

$$C_P = \frac{dq}{dT} = \frac{dh}{dT}$$

$dh = C_p \,.\, dT$

$\Delta h = C_p \,.\, \Delta T$

$Q = \Delta H = m\, C_p\, \Delta T$ ……….*

Notes:

❖ Heat received by the system	q is +ve
❖ Heat rejected by the system	q is _ve
❖ Work done by the system	w is +ve
❖ Work done on the system	w is _ve

Ex10: A certain fluid at 10 bar is contained in a cylinder behind a piston, the initial volume being 0.05 m^3.Calculate the work done by the fluid when it expands reversibly:

a) At constant pressure to a final volume of 0.2 m^3.

b) According to a linear law to a final volume of 0.2 $m^3$and a final pressure of 2 bar.

c) According to a law pv = c to a final volume of 0.1 m^3.

d) According to a law pv^3 = c to a final volume of 0.06 m^3.

e) According to a law p = (A/v^2)_(B/v) to a final volume of 0.1 m^3 and final pressure of 1 bar, A&B are constant.

Ex11: A fluid is heated reversibly at a constant pressure of 1.05 bar until it has a specific volume of 0.1 m^3/kg. it is then compressed reversibly according to a law pv = c to a pressure 4.2 bar, then allowed to expand reversibly according to a law $pv^{1.3}$ = c and finally heated at constant volume back to initial condition. The work done in the constant pressure process is 515 N.m and the mass of fluid present is 0.2 kg. calculate the net work done on or by the fluid in the cycle and sketch the cycle on the pv diagram.

Ex12: Consider the system shown in figure. The initial volume inside the cylinder is 0.1 m^3. At this stats the pressure inside is 100 kpa, which just balance the atmosphere pressure plus the piston weight, the spring is touching but exerts no force on the piston at this state. The gas now heated until the volume is doubled. The final pressure of the gas is 300 kpa, and during the process the spring force is proportional to the displacement of the piston from the initial position. Calculate the work done by the system, what percentage of work is done against the spring.

Ex13: in a turbine of gas turbine unit. The gases flow through the turbine at 17 kg/s and the power developed by the turbine is 14000kw. The enthalpies of the gases at inlet and outlet are 1200 kJ/kg and 360 kJ/kg respectively and the velocity of the gas at inlet and outlet are 60 m/s and 150 m/s respectively. Find the rate at which heat is rejected from the turbine. Find also the inlet pipe cross-sectional area when the inlet specific volume is 0.5 m^3/kg.

Ex14: air flows at a rate of 0.4 kg/s through an air compressor entering at 6 m/s, 1 bar and 0.85 m^3/kg and leaving at 4.5 m/s, 6.9 bar and 0.16 m^3/kg. The internal energy of the air leaving is greater than that of entering air by 88 kJ/kg, cooling water in the jacket surrounding the cylinder absorbs heat from the air at the rate of 59 kJ/s. find the power required to drive the compressor and the inlet and outlet pipe cross-sectional area.

(IDEAL GAS)

(Perfect gas)

Boyle's law:

It is defined as: when a change of state of any gas in which the mass and the temperature remain constant, the volume varies inversely as the pressure.

$$P\alpha\frac{1}{V} \quad \rightarrow \quad P = C\,.\,\frac{1}{V}$$

$$\therefore PV = C\ldots\ldots\ldots\ldots \text{Boyle's law}$$

$$\therefore P_1\,V_1 = P_2\,V_2$$

Ex15: A gas whose original pressure and volume were 300 kN/m^2 and 0.14 m^3 is expanded until its new pressure is 60 kN/m^2 while its temperature remains constant. What is its new volume?

Charles's law:

It is defined as: when the change of state of any gas in which the mass and pressure remain constant, the volume varies in proportion with the absolute temperature.

$$V\,\alpha\,T \quad \rightarrow \quad V = C\,T$$

$$\therefore \frac{V}{T} = C\ldots\ldots\ldots.. \text{charles's law}$$

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

Ex16: A quantity of gas whose original volume and temperature are 0.2 m^3 and 303°C, respectively, is cooled at constant pressure until its volume becomes 0.1 m^3. What will be the final temperature of the gas?

(The characteristic equation of a perfect gas)

The process 1→ A

$$PV = C \dots\dots\dots\dots (\text{Boyle})(T = \text{Const.})$$

$$P_1V_1 = P_AV_A \qquad ,(T_1 = T_A)$$

$$V_A = \frac{P_1}{P_A} . V_1 \ \dots\dots\dots\dots (1)$$

$$V = C\,T \qquad (\text{Charles}) \quad (P = \text{const.})$$

$$\frac{V_A}{T_A} = \frac{V_2}{T_2} = \frac{V}{T} = C$$

$$V_A = \frac{T_A}{T_2} \cdot V_2 \dots\dots\dots\dots (2)$$

From boyle's law $(T_A = T_1)$ sub. in eq. (2)

$$V_A = \frac{T_1}{T_2} \cdot V_2 \dots\dots\dots\dots (3)$$

From eqs. (1)& (3)

$$V_A = \frac{P_1}{P_A} \cdot V_1 = \frac{T_1}{T_2} \cdot V_2 \qquad , \text{from Charles law } P_A = P_2$$

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

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = R \qquad , R = \text{gas constant}$$

$$P_1V_1 = RT_1 \qquad \text{for 1 kg}$$

$$P_1V_1 = mRT_1 \qquad \text{for (m) kg}$$

m = n . M

Where: m= mass kg

n= number of moles mol

M= molecular weight

$PV = mRT$ (In general)

$PV = nMRT$

$MR = \frac{PV}{nT}$ (P& T are constant)

$MR = C \cdot \frac{V}{n}$, $(\frac{V}{n} = C)$ (Avogadro′s theorm)

$\therefore MR = R_\circ$, $R_\circ$ = Universal gas constant

Avogadro's theorem: volume of one mole of any gas is same for all gases at any temperature and pressure.

$$\therefore R_\circ = \frac{PV}{nT}$$

$\because$ Volume of 1 mole at (0°C) and ($P = P_{atm} = 1.0132$ bar) equal to 22.7 m^3.

$$\therefore R_\circ = \frac{1.0132 * 10^5 * 22.7}{1 * (0 + 273)} = 8.314 \quad \frac{kJ}{kg}.K$$

Ex: for $O_2 : R = R_\circ / M = 8314/32 = 0.259$

Ex17: A volume of 3.6 m^3 of O_2 at 220°C and pressure 400 kpa, is compressed reversibly at constant temperature to a final volume of 0.06 m^3. Calculate the mass, the final pressure, the increase in internal energy and the work done.

Joule's law:

It is defined as: the internal energy of a gas is a function of temperature only and is independent of change in pressure and volume.

$$\therefore if \quad T = C \Longrightarrow \Delta u = 0$$

The specific heat capacities of a gas:

a) The constant volume heating of a gas:

Let a mass of gas (m) be heated at constant volume such that its temperature rises from (T_1) to (T_2) and its pressure rises from (P_1) to (P_2). Then

Heat received by the gas = $m\ C_V(T_2 - T_1)$

From NFEE , $Q = \Delta u + W$

$$\because V = C \Longrightarrow W = 0$$

$$Q = \Delta u \quad ,$$

$$or \quad mC_V(T_2 - T_1) = U_2 - U_1$$

From the perfect gas equation (characteristic equation)

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad \Longrightarrow P_2 = P_1\ \frac{T_2}{T_1}$$

Ex18: 2kg of gas, occupying 0.7 m^3, had an original temperature of 15℃. It was then heated at constant volume until its temperature became 135℃. How much heat was transferred to the gas and what was its final pressure?

Take, (C_v = 0.72 kJ/kg .k) & (R = 0.29 kJ/kg .k)

b) The constant pressure heating of a gas:

Let a mass of gas (m) be heated at constant pressure such that its temperature rises from T_1 to T_2 and its volume increases from V_1 to V_2. Then:

Heat received by the gas = $mC_P(T_2 - T_1)$

$$Q = \Delta u + W$$

$$mC_P(T_2 - T_1) = (U_2 - U_1) + P(V_2 - V_1)$$

$$= (U_2 + PV_2) - (U_1 + PV_1)$$

$$= H_2 - H_1$$

Or:

$$U_2 - U_1 = mC_P(T_2 - T_1) - P(V_2 - V_1)$$

When $PV = mRT$ then

$$U_2 - U_1 = mC_P(T_2 - T_1) - mR(T_2 - T_1)$$

$$= m(T_2 - T_1)(C_P - R)$$

From the characteristic equation of a perfect gas:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad , P_1 = P_2$$

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

Note: $H = mC_PT$ $\quad , h = C_PT$ $\quad , \Delta h = C_P\Delta T$

$U = mC_VT$ $\quad , u = C_VT$ $\quad , \Delta u = C_V\Delta T$

Ex19: A gas whose pressure, volume and temperature are 275 kN/m^2, 0.09 m^3 and 185°C, respectively, has its state changed at constant pressure until its temperature becomes 15°C. How much heat is transferred from the gas and how much work is done on the gas during the process?

Take: (R= 0.29 kJ/kg.k) , (C_P= 1.005 kJ/kg.k).

Relation between specific heat (C_p & C_v):

From the non- flow energy equation NFEE

$$Q = W + \Delta u \qquad , \Delta u = mC_V(T_2 - T_1)$$

$$W = \int_1^2 P.dv = P_2V_2 - P_1V_1$$

Ideal Gas Law $\quad PV = mRT$

$$W = mR(T_2 - T_1)$$

$$\therefore Q = mR(T_2 - T_1) + mC_V(T_2 - T_1)$$

$$= m(R + C_V)(T_2 - T_1)$$

$$\because Q = \Delta H = mC_P(T_2 - T_1)$$

$$\therefore mC_P(T_2 - T_1) = m(R + C_V)(T_2 - T_1)$$

$$\therefore C_P = R + C_V \qquad \Longrightarrow \qquad C_P - C_V = R$$

$$\gamma = \frac{C_P}{C_V} \qquad , \gamma = the\ ratio\ of\ the\ specific\ heat.$$

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

$$\gamma - 1 = \frac{R}{C_V} \qquad \Longrightarrow \qquad C_V = \frac{R}{\gamma - 1}$$

$$C_P = \gamma * C_V \qquad \Longrightarrow \qquad C_P = \frac{\gamma R}{\gamma - 1}$$

Ex20: A perfect gas have specific heat as (C_p= 0.846 kJ/kg.k),(C_v= 0.657 kJ/kg.k), find the gas constant and molecular weight of gas.

Ex21: A perfect gas has molecular weight of 26 and a value of (γ)= 1.26, calculate the heat rejected per 1kg when:

a. The gas is contained in originl vessel at 3 bar and 315°C and cooled until the pressure fails to1.5 bar.
b. The gas enters pipe at 280°C and flow steady in the end of the pipe where T=250°C. Neglect any change in velocity of the gas.

Ex22: Five kilogram of oxygen is heated from 250 to 400k at constant pressure. Calculate the change of enthalpy, change in internal energy, heat transferred and work done. $\gamma = 1.4$

Ex23: An oxygen cylinder has a capacity of 300L, and contains O_2 at 3.1 Mpa and 18°C. The value is open and some gas is used. If the pressure and temperature of the oxygen fall to 1.7 Mpa and 15°C respectively. Find the mass of oxygen used. If after the value is closed the oxygen remain in the cylinder is gradually attains its initial temperature of 18°C. Find the amount of heat transfer through the cylinder wall, oxygen density at 0°C and 0.1013 Mpa is 1.429 kg/m^3 and $\gamma = 1.4$

Sheet No. 2

Reversible and Irreversible Processes for the Ideal Gas

1. ***Reversible non-flow processes:***

a. **Constant volume process (isometric)**

From the non-flow E.E.

$$Q = W + \Delta u$$

$$W = \int PdV \qquad , V = C \Longrightarrow dV = 0$$

$\therefore W = 0 \Rightarrow Q = \Delta u$

$Q = mC_V(T_2 - T_1)$

b. Constant pressure process (isobaric)

From the NFEE

$Q = W + \Delta u$

$W = P_2V_2 - P_1V_1$

$= mR(T_2 - T_1)$

$\Delta u = mC_V(T_2 - T_1)$

$Q = mR(T_2 - T_1) + mC_V(T_2 - T_1)$

$= m(R + C_V)(T_2 - T_1)$

$= mC_P(T_2 - T_1) = \Delta H = m(h_2 - h_1)$

$Q = mC_P(T_2 - T_1)$

c. Constant temperature process (isothermal)

From NFEE:

$Q = W + \Delta u$

$$W = \int_1^2 PdV$$

we have $\dfrac{P_1V_1}{T_1} = C$, since $T = C$

$\therefore P_1V_1 = C \Rightarrow P = \dfrac{C}{V}$

$$W = \int_1^2 \frac{C}{V}\, dV = C\ \ln\frac{V_2}{V_1}$$

$$W = PV\ln\frac{V_2}{V_1} = mRT_1 \ln\frac{V_2}{V_1}$$

$$U_2 - U_1 = mC_V(T_2 - T_1) \qquad , \qquad T_2 = T_1 \Longrightarrow \Delta U = 0$$

$$\therefore Q = PV\ln\frac{V_2}{V_1} = PV\ln\frac{P_1}{P_2} = mRT\ln\frac{P_1}{P_2}$$

Ex24: 1kg of nitrogen (Molecular weight 28) is compressed reversibly and isothermally from 1.01 bar, 20°C to 4.2 bar. Calculate the work done and the heat flow during the process. Assume nitrogen to be a perfect gas.

d. A diabatic process:

In this process the system must be in thermal insulated, to prevent the heat transfer between the system and surrounding.

To find the relation between P & V from the non-flow E.E

$$Q = W + \Delta u$$

$$adiabatic\ process \Longrightarrow Q = 0$$

$$dQ = dU + dW \Rightarrow dq = du + dw$$

$dU = mC_V dT \Longrightarrow du = C_V dT$ (Per unit mass)

$$dW = PdV \Longrightarrow dw = pdv$$

$$\therefore dq = C_V dT + Pdv$$

$$pv = RT \Longrightarrow P = RT/v$$

$$\therefore dq = C_V dT + RT\frac{dv}{v} = 0$$

$$0 = C_V dT + RT\frac{dv}{v}$$

$$0 = C_V\frac{dT}{T} + R\frac{dv}{v}$$

$$0 = \frac{dT}{T} + \frac{R}{C_V}\cdot\frac{dv}{v} \qquad , \qquad \frac{R}{C_V} = \gamma - 1$$

$$0 = \frac{dT}{T} + (\gamma - 1)\frac{dv}{v}$$

$$\int 0 = \int_{T_1}^{T_2}\frac{dT}{T} + (\gamma - 1)\int_{v_1}^{v_2}\frac{dv}{v}$$

$$\ln T + (\gamma - 1)\ln V = C \qquad , \qquad T = \frac{Pv}{R}$$

$$\ln\frac{Pv}{R} + (\gamma - 1)\ln v = C$$

$$\ln\frac{Pv\cdot v^{(\gamma-1)}}{R} = C$$

$$\frac{Pv^{\gamma}}{R} = e^{c} \Rightarrow Pv^{\gamma} = Re^{c} = C$$

$\therefore PV^{\gamma} = C$ adiabatic process

The non-flow energy

$$Q = W + \Delta U \qquad , Q = 0 \quad (adiabatic)$$

$$W = -\Delta U$$

$$= mC_V(T_1 - T_2) = m\left(\frac{R}{\gamma - 1}\right)(T_1 - T_2)$$

$$W = \frac{mR(T_1 - T_2)}{\gamma - 1}$$

$$W = \frac{P_1V_1 - P_2V_2}{\gamma - 1} \qquad \textit{Adiabatic work}$$

The Relation Between P, V and T in Adiabatic Process:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = C$$

$$\frac{P_1}{P_2} = \frac{V_2}{V_1} \cdot \frac{T_1}{T_2} \ldots\ldots\ldots\ldots(1)$$

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

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{\gamma} \ldots\ldots\ldots\ldots(2)$$

$$Sub.eq(1)\ in\ eq\ (2)$$

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

$$\therefore \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} \ldots\ldots\ldots\ldots(3)$$

$$Sub.eq(2)\ in\ eq\ (3) \qquad , where\ \frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}}$$

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

$$\therefore \frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} \qquad the\ relation\ between\ P, v\ and\ T$$

$$for\ adiabatic\ process$$

Ex25: air at 1.02 bar, 22°C, initially occupying a cylinder volume of 0.015m^3, is compressed reversibly and adiabatically by a piston to a pressure of 6.8bar. Calculate the final temperature, the final volume, and the work done on the mass of air in the cylinder.

e. Polytropic processes:

This general case of expansion or compression of a substance according to the law $PV^n = C$, it is called a polytropic expansion or compression or a polytrope.

It is should be noted that the value of the constant "C" will change with change with each change of condition , so also will the value of "n" which is called the "index" of the expansion or compression or the polytropic exponent.

$PV^n = C$

The non-flow energy equation

$Q = W + \Delta U$

$$W = \int PdV = C\int \frac{dV}{V^n} = PV^n \int (V^{-n})\, dV$$

$$W = PV^n \left[\frac{V^{-n+1}}{-n+1}\right]_1^2 = \frac{P_2V_2^n . V_2^{-n+1} - P_1V_1^n . V_1^{-n+1}}{-n+1}$$

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

$$W = \frac{P_1V_1 - P_2V_2}{n-1}$$

$$W = \frac{mR(T_1 - T_2)}{n-1}$$

$\Delta U = mC_V(T_2 - T_1) = -mC_V(T_1 - T_2)$

$$\Delta U = -m(R/\gamma - 1)(T_1 - T_2)$$

$$\therefore Q = \frac{mR(T_1 - T_2)}{n-1} - m\frac{R}{\gamma - 1}(T_1 - T_2)$$

$$= mR(T_1 - T_2)\left(\frac{1}{n-1} - \frac{1}{\gamma - 1}\right)$$

$$mR(T_1 - T_2)\left(\frac{\gamma - 1 - n + 1}{(n-1)(\gamma - 1)}\right)$$

$$= mR(T_1 - T_2)\left(\frac{\gamma - n}{(n-1)(\gamma - 1)}\right)$$

$$= (mR(T_1 - T_2)/n - 1)(\gamma - n/\gamma - 1)$$

$$\therefore Q = \left(\frac{\gamma - n}{\gamma - 1}\right).W$$

In a polytropic process the value of (n) depends on the mount of heat added or rejected and on the work done during the process.

$$PV^n = C$$

When:

1. $n = 0 \rightarrow PV^0 = C \rightarrow P = C \qquad (isobaric)$
2. $n = 1 \rightarrow PV^1 = C \rightarrow PV = C \qquad (isothermal \quad T = c)$
3. $n = \gamma \rightarrow PV^\gamma = C \rightarrow Q = 0 \qquad (adiabatic)$
4. $n = \infty \rightarrow PV^\infty = C \rightarrow P^{\frac{1}{\infty}}.V = C \rightarrow V = C \qquad (isometeric\ or\ isochoric)$

Processes:

$1 \rightarrow A \qquad cooling\ at \quad P = C$

$1 \rightarrow A^- \qquad heating\ at \quad P = C$

$1 \rightarrow B^- \qquad expansion\ at \qquad T = C$

$1 \rightarrow B \quad compression\ at \quad T = C$

$1 \rightarrow C \quad adiabatic\ compression \quad (PV^{\gamma} = C)$

$1 \rightarrow C^{-} \quad adiabatic\ expansion$

$1 \rightarrow D \quad heating\ at \quad V = C$

$1 \rightarrow D^{-} \quad cooling\ at \quad V = C$

Work and the hyperbolic process:

The hyperbolic process is a particular case of the polytropic process, $(PV^{n} = C)$, being the case when (n=1). Thus, the law for the hyperbolic process is,

$$PV = C$$

For a hyperbolic change from state 1 to state 2,

$$P_1V_1 = P_2V_2$$

An expression for the work done during a polytropic process has already been determined,

$$work\ done = \frac{P_1V_1 - P_2V_2}{n-1}$$

$$for\ hyperbolic\ process, \quad P_1V_1 = P_2V_2 \quad \& \quad n = 1$$

$$\therefore work\ done = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{0}{0}$$

∴ to compute the work done, it is necessary to determine the area under curve.

$$work\ done = \int_{V_1}^{V_2} PdV$$

$$PV = C \quad \Rightarrow \quad P = C/V$$

$$W = C\int_{V_1}^{V_2}\frac{dV}{V} \qquad = C\,[\ln V]_{V_1}^{V_2}$$

$$W = C[\ln V_2 - \ln V_1]$$

$$= C\;\ln\frac{V_2}{V_1} \qquad = PV\;\ln\frac{V_2}{V_1}$$

$$\therefore W = PV\;\ln\frac{V_2}{V_1}$$

Ex26:A gas is compressed hyperbolically from a pressure and volume of 100 kN/m^2 and 0.056m^3, respectively to a volume of 0.007m^3. Determine the final pressure and the work done on the gas.

2-Irreversible processes (closed system)

a. Paddle work (P = c)

w_p = paddle work

from NFEE

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

Q: may be equal to zero if the process is very fast or insulated.

$$\Delta U = mC_V\,(T_2 - T_1)$$

$$W = P(V_2 - V_1) = mR(T_2 - T_1)$$

$W_P = -ve$ since it is done on the system.

b. Paddle work (V = c)

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

$$\Delta U = mC_V\,(T_2 - T_1)$$

$W_P = -ve$ (done on the system)

3. Reversible processes (open system)

a. **Constant pressure process:** (such as condenser)

$$gz_1 + p_1v_1 + u_1 + \frac{1}{2}c_1^2 + q = gz_2 + p_2v_2 + u_2 + \frac{1}{2}c_2^2 + w$$

$$P_1 = P_2$$

$$w - q = (P_1V_1 - P_2V_2) + (U_1 - U_2) + \frac{1}{2}(C_1^2 - C_2^2) * 10^{-3} + g(Z_1 - Z_2) * 10^{-3}$$

or:

$$W^{\cdot} - Q^{\cdot} = m^{\cdot}[w - q]$$

b. **Constant temperature process:**

$$T = c\,, \quad P_1V_1 = P_2V_2 \quad ,U_1 = U_2$$

$$\therefore w = q + \left[g(z_1 - z_2) + \frac{1}{2}(C_1^2 - C_2^2)\right] * 10^{-3}$$

or $\quad w = \int_1^2 pdv = pv\,ln\frac{v_2}{v_1} = mRT\,ln\frac{v_2}{v_1}$

c. **Polytropic process:**

From steady flow energy equation (SFEE)

$$w - q = (P_1V_1 - P_2V_2) + (U_1 - U_2) + \frac{1}{2}(C_1^2 - C_2^2) * 10^{-3} + g(Z_1 - Z_2) * 10^{-3}$$

4. ***Irreversible processes (open system)***

a. **Unresisted, or free, expansion:**

$$Q = W + \Delta U$$

$Q = 0$ (adiabatic) ,W=0

$$\therefore \Delta U = 0 \Longrightarrow U_2 = U_1 \quad (per\ 1kg)$$

$$C_VT_2 = C_VT_1$$

$$\therefore T_1 = T_2\ (Irreversible)$$

Ex27: Air at 20 bar is initially contained in vessel "A" as shown in the fig. above, the volume of which can be assumed to be 1m^3. The valve X is opened and air expands to fill vessels A and B. Assuming that the vessels are of equal volume, Calculate the final pressure of the air.

b. Throttling process:

A flow of fluid is said to be throttled when there is some restriction to the flow, when the velocities before and after the restriction are either equal or negligibly small, and when there is a negligible heat loss to the surroundings.

From SFEE:

$$gz_1 + p_1v_1 + u_1 + \frac{1}{2}c_1^2 + q = gz_2 + p_2v_2 + u_2 + \frac{1}{2}c_2^2 + w$$

$$Z_1 = Z_2 \quad ,W = 0 \quad ,Q = 0 \quad ,C_1 \cong C_2$$

$$\therefore\ P_1V_1 + U_1 = P_2V_2 + U_2$$

$$h_1 = h_2 \Longrightarrow C_p\,T_1 = C_p\,T_2$$

$$\therefore T_1 = T_2 \qquad (Irreversible)$$

c. Adiabatic mixing:

$$m_1 + m_2 = m_3 \qquad (mass\ conservation)$$

$$\dot{m}_1h_1 + \dot{m}_2h_2 = \dot{m}_3h_3 \qquad (energy\ conservation)$$

$$\dot{m}_1C_pT_1 + \dot{m}_2C_pT_2 = \dot{m}_3C_pT_3$$

For the same gases mixing $\qquad$ C_p = constant

$$\dot{m}_1T_1 + \dot{m}_2T_2 = \dot{m}_3T_3$$

$$\dot{m}_1T_1 + \dot{m}_2T_2 = (\dot{m}_1 + \dot{m}_2)T_3$$

Ex28: 0.05 kg of air is heated at constant pressure of 2bar until the volume occupied is 0.0658m^3. Calculate the heat supplied and work done, when the initial temperature is 130℃. Take C_p = 1.005 kJ/kg.k , R=0.287 kJ/kg.k

Ex29: A constant pressure adiabatic system contain 0.13 kg of air at 1.3 bar. The system receives paddle work. The temperature of air rises from 29 to 185℃. Find the total work, mechanical work, change in internal energy and enthalpy. Take $(R = 0.287 \quad ,\gamma = 1.4)$.

Ex30: Air at 1.02bar and 22℃ initially occupying a cylinder of 0.015m^3, is compressed reversibly and adiabatically by a piston to a pressure of 6.8 bar. Calculate the final volume, the final temperature and the work done on the mass of air in the cylinder.

Sheet No.3

(Steam and Two-Phase System)

Steam: is a vapour of water, and is invisible when pure and dry. It is used as the working substance in the operation of steam engines and steam turbines. Steam does not obey laws of perfect gases, until it is perfectly dry.

Formation of steam at constant pressure from water:

Consider 1kg of water at 0℃ contained in the piston cylinder arrangement as shown in the figure (a).

The piston and weights maintain a constant pressure in the cylinder. If we heat the water contained in the cylinder, it will be converted into steam as below:

1- The volume of water will increase slightly with the increase in temperature as shown in fig (b). It will cause the piston to move slightly upwards and hence work is obtained. This increase in volume of water (or work) is generally, neglected for all types of calculation.
2- On further heating, temperature reaches boiling point. The boiling point of water, at normal atmospheric pressure of 1.013 bar is 100℃, but it increases with the increase in pressure. When the boiling point is reached, the temperature remains constant and the water evaporates, thus pushing the piston up against the constant pressure. Consequently, the specific volume of steam increase as shown in fig (c). At this stage, the steam will have some particles of water in suspension, and is termed as "Wet Steam". This process will continue till the whole water is converted into wet steam.
3- On further heating, the particles in suspension will be converted into steam. The entire steam, in such a state, is termed as dry steam or saturated steam as shown in fig (d). Practically the dry steam behaves like a perfect gas.
4- On further heating, the temperature of the steam starts rising. The steam, in such a state is termed as superheated steam as shown in fig. (e).

Temperature vs. Total Heat Graph during Steam Formation:

The process of steam formation may be represented on a graph, whose abscissa represents the total heat and the vertical ordinate represents the temperature. The point (A) represents the initial condition of water at 0℃ and pressure P (in bar) as shown in figure below. Line ABCD shows the relation between temperature and heat at a specific of P (in bar).

During the formation of the superheated steam, from water at freezing point, the heat is absorbed in the following three stages:

1- The heating of water up to boiling temperature or saturation temperature (t) is shown by AB. The heat absorbed by the water is AP, known as sensible heat (S.H.) or liquid heat or total heat of water.
2- The change of state from liquid to steam is shown by BC. The heat absorbed during this stage is PQ, known as latent heat (L.H.) of vaporization.
3- The superheating process is shown by CD. The heat absorbed during this stage is QR, known as heat of superheat (H.S.). Line AR represents the total heat of the superheated steam.

If the pressure is increased (say P_1 bar), the boiling temperature also increase. The point (E) represents the boiling temperature or saturation temperature at pressure (P_1) and (F) is the point of dry saturated steam, line (FG) shows the constant pressure process, in which the steam is superheated.

The line passing through the points A, B, E, and K is known as "saturated liquid line" which forms boundary line between water and steam. Similarly, a line passing through dry steam point L, F, C is known as "dry saturated steam line" which forms boundary line between wet and superheated steam.

It may also be noted from the figure, that when the pressure and saturation temperature increases, the latent heat of vaporization decreases. It becomes zero at point (N) where liquid and dry steam lines meet.

This point (N) is known as the critical point and at this point, the liquid and vapour phases merge. The temperature corresponding to critical point (N) is known as critical temperature and the pressure is known as critical pressure. For steam, the critical temperature is 374.15℃ and critical pressure is 221.2bar.

Important Terms for Steam:

1- **Wet steam:**
When the steam contains moisture or particles of water in suspension, it is said to be **wet steam**. It means that the evaporation of water is not complete, and the whole of the latent heat has not been absorbed.

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

steam has absorbed its full latent heat and behaves practically, in the same way as a perfect gas.

3- **Superheated Steam:**

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

4- **Dryness fraction or quality of wet steam:**

It is the ratio of the mass of actual dry steam to the mass of same quantity of wet steam, and generally denoted by "x",

Mathematically, $x = \frac{mg}{mg+mf} = \frac{mg}{m}$

mg = mass of actual dry steam.
mf = mass of water in suspension, and
m = mass of wet steam.

5- **Sensible heat of water:**

It is the amount of heat absorbed by 1 kg of water, when heated at a constant pressure, from the freezing point (0°C) to the temperature of formation of steam. The sensible heat is also known as liquid heat.

The specific heat of water at constant pressure is usually taken as (4.2 kJ/kg.k).

$Q_{sensible}$ = mass * Specific heat * Rise in temp.

$$= mC_P(T_2 - T_1)$$

$$= m(h_2 - h_1)$$

$$= H_2 - H_1$$

$h_2, h_1 \equiv Enthalpy\ of\ fluid\ (water), denoted\ by\ h_f$

6- Latent heat of vaporization:

It is the amount of heat absorbed to evaporate 1 kg of water, at its boiling point or saturation temperature without change of temperature. It is denoted by h_{fg} and its value depends upon the pressure.

The heat of vaporization of water or latent heat of steam is 2257 kJ/kg at atmospheric pressure. It has been experimentally found that the value of h_{fg} decreases as the pressure increases and it is **zero** at critical pressure.

If the steam is wet with a dryness fraction (x), then the heat absorbed by it during evaporation is ($x\ h_{fg}$).

7- Enthalpy or total heat of steam:

It is amount of heat absorbed by water from freezing point to saturation temperature plus the heat absorbed during evaporation

∴ Enthalpy or total heat 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 follows:

i. **Wet steam:** the enthalpy of wet steam is given by:

$$h = h_f + xh_{fg}$$

$$h_f = u_f + p\vartheta_f$$

ii. **Dry steam:** we know that in case of dry steam, (x = 1)

$$\therefore \quad h = h_f + 1 * h_{fg}$$

$$= h_f + (h_g - h_f)$$

$$h = h_g$$

iii. **Superheated steam:** if we further add heat to the dry steam, its temperature increases while pressure remaining constant. This increase in temperature shows the superheat stage of the steam. Thus, the total heat required for the steam to be superheated is:

h_{sup} = total heat for dry steam + heat for superheated steam

$$= h_f + h_{fg} + C_P(t_{sup} - t) = h_g + C_P(t_{sup} - t)$$

Where:

C_P = specific heat at constant pressure for superheated.

t_{sup} = temperature of the superheated steam.

t = saturation temperature at the given constant pressure.

Notes: 1- The difference (t_{sup} _t) is known as degree of superheated

2- The value of C_p for steam lies between (1.67 kJ/kg. k) to (2.5 kJ/kg. k).

8- 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 in kg/m^3.

The value of specific volume decreases with the increase in pressure.

The expressions for the volumes occupied by steam are as follows:

- **Wet steam:** consider 1kg of wet steam of dryness fraction x. when know that this steam will have (x kg) of dry steam and $(1 - x)$kg of water. Let ϑ_f be the volume of 1kg of water, then

Volume of one kg of wet steam = $x\vartheta_g + (1 - x)\vartheta_f$

Since ϑ_f is very small as compared to ϑ_g, therefore the expression $(1-x)\vartheta_f$ may be neglected.

∴ volume of one kg of wet steam = $x.\vartheta_g \quad m^3$

Or specific volume of wet steam, $\quad \vartheta = x.\vartheta_g \quad m^3/kg$

- **Dry steam:** we know that in case of dry steam, the mass of water in suspension is zero and dryness fraction is unity. Therefore
  Specific volume of dry steam = $\vartheta_g \quad m^3/kg$
- **Superheated steam:** we have already discussed that when the dry saturated steam is further heated under a constant pressure, there is an increase in volume with the rise in temperature.

The superheated steam behaves more or less like a perfect gas. Therefore, according to Charle’s law,

$$\frac{\vartheta_{sup}}{T_{sup}} = \frac{\vartheta_g}{T} \qquad or \qquad \vartheta_{sup} = \frac{\vartheta_g * T_{sup}}{T}$$

Where:

ϑ_{sup} = specific volume of superheated steam.

ϑ_g = specific volume of dry steam at the pressure of steam formation.

T_{sup} = absolute temperature of superheated steam.

T = absolute saturation temperature at the pressure of steam formation.

Ex31: Calculate the enthalpy of (1kg) of steam at a pressure of (8 bar) and dryness fraction of (0.8). How much heat would be required to raise (2kg) of this steam from water at (20℃)?

Ex32: Determine the quantity of heat required to produce (1kg) of steam at a pressure of (6 bar) at a temperature of (25℃), under the following conditions:

1- When the steam is wet having a dryness fraction (0.9).
2- When the steam is dry saturated.
3- When it is superheated at a constant pressure at (250℃) assuming the mean specific heat of superheated steam to be (2.3 kJ/kg. k).

Ex33: Determine the condition of steam in the following cases:

1- At a pressure of 10 bar and temperature 200℃.
2- At a pressure of 10 bar and volume 0.175 m^3/kg