

# UNIT - 1

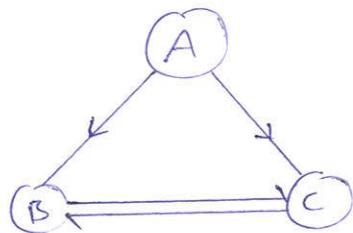
## TEMPERATURE

Introduction - Temperature and heat describes whether a body is hot or cold.

Two bodies are said to be in thermal equilibrium if no heat transfer takes place b/w them when they are placed in contact.

### Zeroth Law of Thermodynamics

When a body 'A' is in thermal equilibrium with a body 'B' and also separately with a body 'C', then B and C will be in thermal equilibrium with each other.



Zeroth law tests equality of temperature with-

- out actually bringing the system in thermal contact.

Concept of equality of temperature - when a <sup>hot</sup> body is kept in contact with a cold body, the cold body warms and hot body cools down, thus the energy is transferred from hot body to cold body. The transfer will continue until the temperature of both bodies become equal. At this point the two bodies are said to be in a state of thermal equilibrium. This is known as equality of temperature.

and forms the basis for measurement of temperature.

∴ two bodies have equality of temperature if, when they are in thermal communication, no change in any observable property occurs.

Principles of thermometry:-

Thermometer:- the reference body which is used in the determination of temperature is called the thermometer.

(OR)

It is a device of measuring temperature with scientific precision.

∴ the selected characteristic is called the thermometric property.

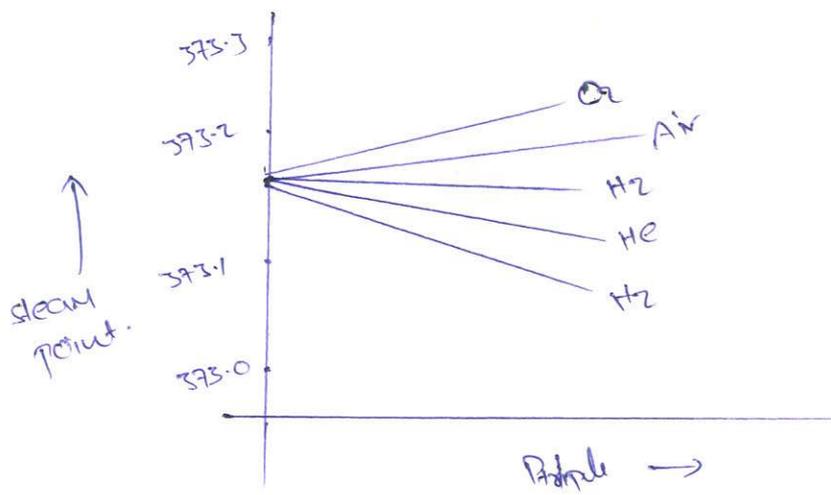
Thermometry:- thermometry is defined as the art of device of measuring temperature with scientific precision.

The basic principle of thermometry is that the two bodies in contact and in thermal equilibrium have same temperature.

A property which changes in value as a function of temperature is called thermometric property.

The substance with thermometric property is called the thermometric substance.

unit-2, Pg -2/40



The temperature of a steam bath (steam point) as measured by placing different gases in different amounts. on the horizontal axis the  $P_{tri}$  of the gas is taken at the triple point of water. This is almost proportional to the mass of the gas present. From the figure it is observed that different gas thermometers measure steam point differently at a given pressure. However this difference decreases as the amount of gas decreases and hence  $P_{tri}$  decreases. In the limit  $P_{tri}$  tending to zero, '0' all the gas thermometers give the same value 373.16 K for steam point. So we define a temperature scale as ~~follows~~

$$T = \lim_{P_{tri} \rightarrow 0} \frac{P}{P_{tri}} \times 273.16 \text{ K.}$$

when we take the small amount

of gas in a gas thermometer the scale is almost identified to the above equation. This scale is known as ideal gas temperature scale and is independent of the gas chosen. However it may depend on the properties of gases in general.

The unit of this temperature is called kelvin & and is abbreviated as K. The ideal gas temperature scale happens to be identical with the absolute scale and hence we use 'K' to denote this unit.

### first law of thermodynamics

Introduction - As zeroth law of thermodynamics gives the concept of temperature. first law of thermodynamics gives the concept of internal energy.

first law of thermodynamics is often called as law of conservation of energy, when it is used for analysis of system involving heat and work.

### law of conservation of energy - [1st law of T.D.]

law of conservation of energy which states that energy can neither be created nor destroyed but can be converted ~~into~~ one form to another form.

It means two forms of energy heat and work are mutually convertible. The first law of thermodynamics is more elaborately stated for i) closed system

ii) open system.

iii) isolated system.

Further in a closed system a substance can undergo a cyclic process or simply a change of state.

$$T = 273.16 \frac{x}{x_t}$$

→ standard fixed point of thermometry.

applying this principle to various thermometers

\* constant volume gas thermometer

$$T(P) = 273.16 \frac{P}{P_t}$$

\* constant pressure gas thermometer

$$T(V) = 273.16 \frac{V}{V_t}$$

\* electric resistance thermometer.

$$T(R) = 273.16 \frac{R}{R_t}$$

\* thermo couple

$$T(E) = 273.16 \frac{E}{E_t}$$

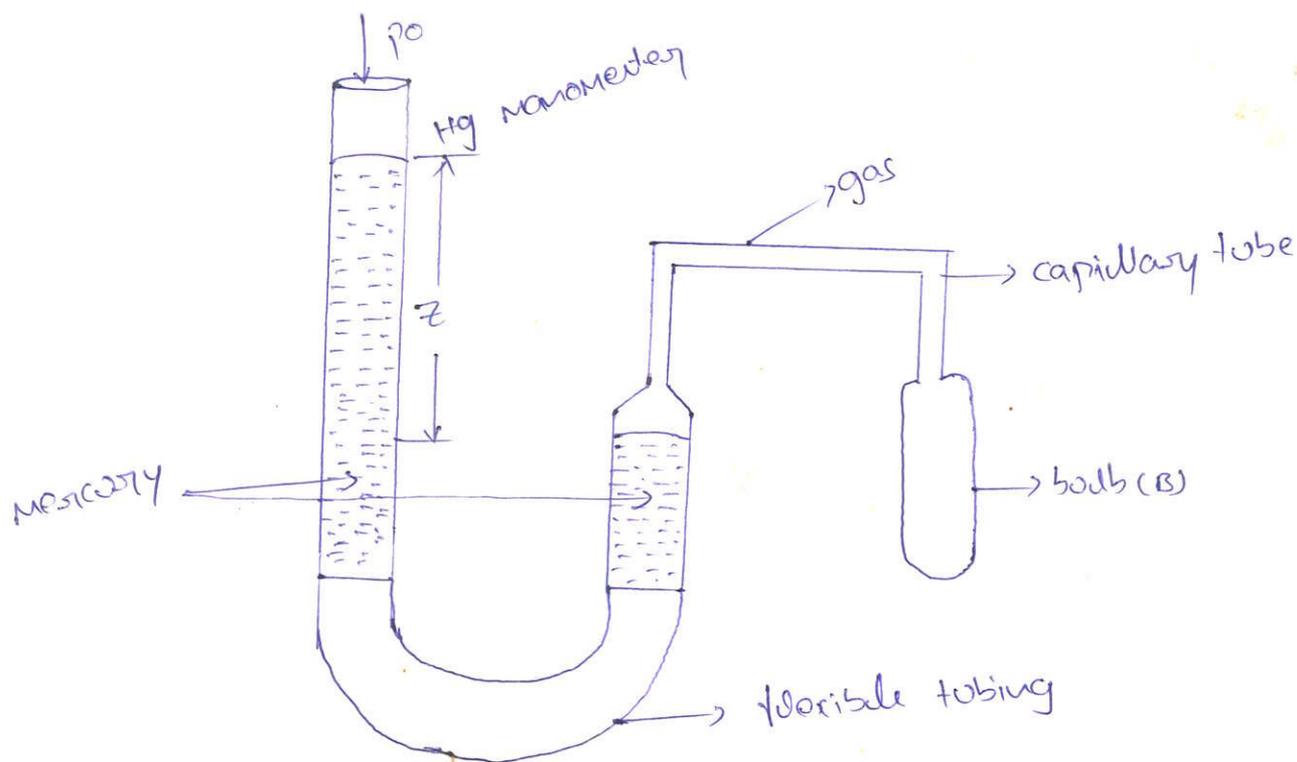
\* liquid - in - glass thermometer

$$T(L) = 273.16 \frac{L}{L_t}$$

∴

constant volume gas thermometer

A glass enclosed in a container has a definite volume and a definite pressure at any given state. If the volume is constant it increases the pressure of gas with increasing temperature. This property is used in measuring temperature by using a constant volume gas thermometer.



A small amount of gas is enclosed in bulb B which is in communication with Hg. The other limb of the Hg is open to atmosphere. The pressure in the bulb can be used as thermometric property and shown in fig.

$$P = P_0 + P_{Hg} z$$

When the bulb is exposed to high temperature or low temperature the volume of the gas changes and to keep this volume constant the Hg levels have to be adjusted by moving the bulb and becomes the thermodynamic property. This will change the pressure of the gas.

Let us assume that temperature is proportional to the pressure (ie)  $T \propto P$ , where  $\propto$  is a constant. In addition the temperature of triple point of water is assigned

Thermometry involves

- (i) construction of thermometer.
- (ii) calibration of thermometer.
- (iii) sensitiveness of thermometer.

Construction of thermometer:- The thermometer is based on the thermometric property. The thermometric substance is selected on the basis of range of temperature to be measured and accuracy of result desired.

Thermometers and thermometric properties

| <u>S.No</u> | <u>Thermometer</u>                | <u>Thermometric Property</u> | <u>Symbol</u> |
|-------------|-----------------------------------|------------------------------|---------------|
| 1.          | constant volume gas thermometer   | pressure                     | P             |
| 2.          | constant pressure gas thermometer | volume                       | V             |
| 3.          | electric resistance thermometer   | Resistance                   | R             |
| 4.          | thermo couple                     | thermal e.m.f                | E             |
| 5.          | mercury in glass thermometer      | length                       | l             |

Calibration of thermometer

To calibrate the thermometer, two reference points are selected.

- (i) ice point
- (ii) steam point.

Ice point is temperature at which pure ice coexisted in equilibrium with air-saturated water at one atmospheric pressure.

Steam point is the temperature of co-existence in equilibrium b/w pure water and pure steam at one atmospheric pressure. The temperature interval b/w these two fixed points is divided into equal parts which are assigned numerical values of temperature, known as "thermometric scale".

Use of reference points - After 1954, the reference point is the triple point of water (the state at which ice, liquid water and water vapour exist in equilibrium.

Temperature at this state = 273.16 K

$$\Theta_t \propto x_t$$

$$\therefore \Theta_t = a x_t$$

$$a = \frac{\Theta_t}{x_t} = \frac{273.16}{x_t}$$

where  $\Theta_t$  = triple point of water

$a$  = arbitrary constant.

$x_t$  = thermometric property.

$$\therefore \tau_{\Theta} = a x$$

$\tau$  = temperature measured

$$\tau = \frac{273.16}{x_t} \cdot x$$

A value of  $273.16 \text{ K}$ . Triple point is defined as the state in which a substance exists in all of its three phases. The unit 'K' is known as kelvin. To measure the value of  $t$  we expose the bulb to ~~the~~ the triple point cell and obtain

$$C = \frac{273.16 \text{ K}}{P_{\text{triple point}}}$$

$$\text{thus } T = 273.16 \times \frac{P}{P_{\text{triple point}}}$$

To measure the temperature of a bath the bulb is dipped in the bath. sufficient time is allowed so that the gas in the bulb comes to thermal equilibrium with the bath. the right limb of the manometer is adjusted to bring the volume of the gas to its original value and the pressure  $p$  of the gas is measured with the manometer. The temperature ' $T$ ' of the gas scale is obtained from the above equation.

### Scales of temperatures:-

The two scales of temperature used mostly for measuring are.

- i) Fahrenheit scale
- ii) Celsius scale.

These two scales are based on number of divisions between ice point and steam point of water at standard atmospheric pressure.

Fahrenheit scale has 180 units between these reference points whereas Celsius scale has 100 units. Zero points on scales are arbitrary. Second law of thermodynamics defines absolute scale of temperature.

The absolute Fahrenheit scale is called as Rankine scale whereas the absolute Celsius scale is termed as Kelvin scale. The zero points on both absolute scales show same physical state and

$$\left(\frac{T_2}{T_1}\right)_{\text{Rankine}} = \left(\frac{T_2}{T_1}\right)_{\text{Kelvin}}$$

Relation b/w scales of temperature is

$$\frac{O_C}{100} = \frac{O_F - 32}{180}$$

or

$$O_C = \frac{5}{9} [F - 32] \quad \text{--- (1)}$$

$$O_C = K - 273.16$$

$$O_R = O_F + 459.67 \quad \text{--- (2)}$$

$$K = O_C + 273.16 \quad \text{--- (3)}$$

$$R = 9/5 \text{ } ^\circ K \quad \text{--- (4)}$$

Ideal gas temperature scale

The temperature scale defined by the above equation depends on the gas used its amount present in the thermometer.

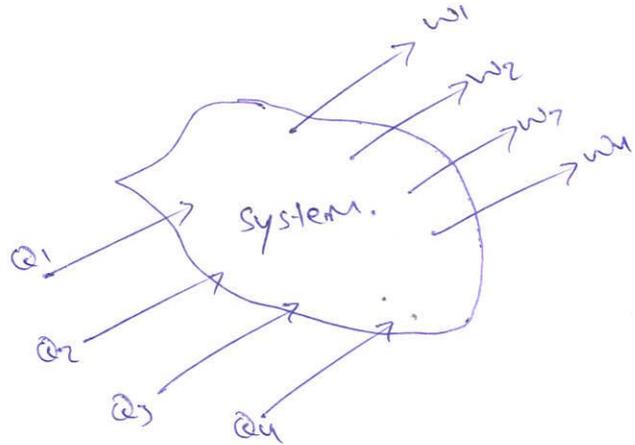
First law of thermodynamics :- [process].

when a system is under going a cyclic process  
- the net heat transfer through the system is equal to  
work transfer.

$$Q_1 + Q_2 + Q_3 + Q_4 = W_1 + W_2 + W_3 + W_4$$

$$\oint dq = \oint dw$$

(or)



algebraic sum of all heat transfers are equal to

~~Q~~ algebraic sum of work transfer.

Internal energy :- the energy stored in the substance is called internal energy.

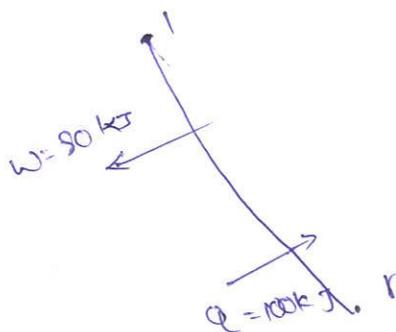
In cyclic process :- the internal energy will be change.

$dq$  = heat transfer

$dw$  = work transfer

$$dq = du + dw \text{ (process)}$$

heat transfer = internal energy + work transfer.



process 1 → 2

$$Q = 100 \text{ kJ}$$

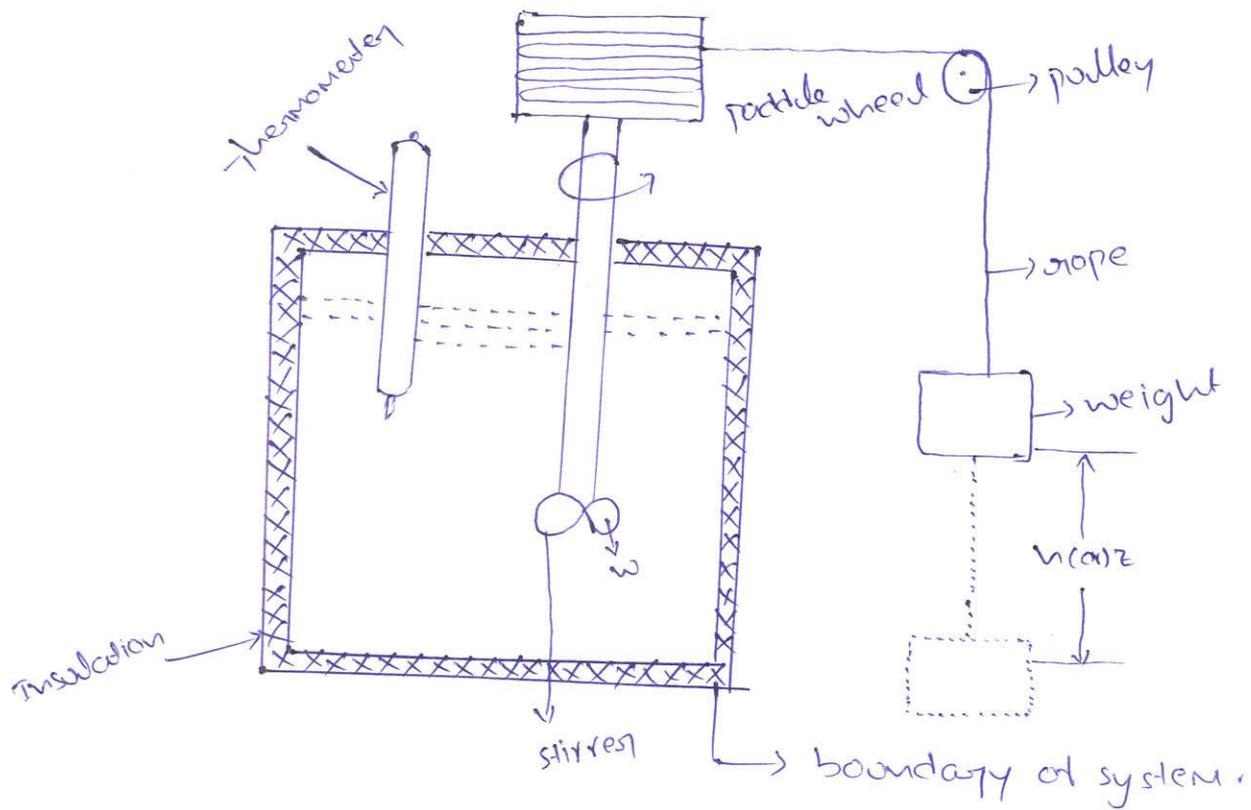
$$dw = 20 \text{ kJ}$$

$$W = 80 \text{ kJ}$$

∴ stored energy = internal energy.

## Joule's experiment

[variation of first law of T.O]



Joule conducted experiments which uses the first step

in the analysis of thermodynamic system. This is applicable to a closed system undergone by a cycle. Joule has taken an insulated vessel filled with certain quantity of liquid as shown to measure the temperature of liquid, he has inserted a thermometer and to churn the fluid a stirrer is placed. by lowering the weight ( $w$ ) through a distance ' $z$ ' the work is done on the system by stirring the paddle. The work input to the fluid causes a rise in temperature of the fluid. The amount of work done is obtained by the product of ' $w$ ' and ' $z$ ' by producing small opening in container insulation the heat is then allowed to transfer from the liquid to the surroundings [may be to another liquid to

to lowest temperature. till the temperature of the system attains its original value. Thus the system is first made to undergo a change from its original value. Thus the system is first made to undergo a change from its initial state by introducing work and allowing the liquid again to return to its original state by removed to heat represents a cyclic process. This is a closed system undergoing a cyclic process.

$$\oint dq = \oint dw$$

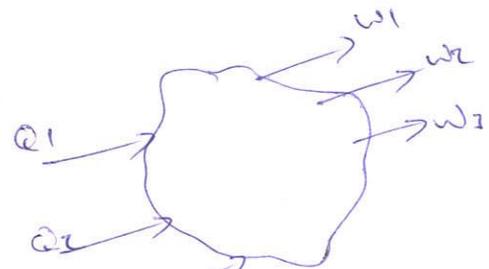
$$\oint dq = J \oint dw$$

where  $J$  is Joules constant.

The value of  $J$  in metric units is  $426.7 \text{ kgf/kcal}$  and in SI units  $1 \text{ Nm/J}$ .

The above equation can be written as

$$\oint dq = \oint dw$$



Let us apply this to a closed

system undergoing a cyclic process

with  $3$  work and  $3$  heat interactions as shown.

we can write

$$q_1 + q_2 + q_3 = w_1 + w_2 + w_3$$

∴ The first law of thermodynamics for a closed system undergoing a cyclic process states that the net amount of heat transfer is equal to the net amount of work done.

Corollaries means applications :-

First law of thermodynamics - corollaries :-

- \* Internal energy is a property of a system (or) point function (or)
- \* specific heat at constant volume (or)
- \* Enthalpy (H or h)
- \* specific heat at constant pressure (or)
- \* Energy of an isolated system is constant.
- \* perpetual motion machine of first kind PMM-1 is

Impossible  
∴

Control volume - for any system and any process, the first law can be written as

$$Q = \Delta E + W$$

where  $E$  represents all forms of energy stored in the system for a pure substance.

$$E = E_K + E_P + U$$

where  $E_K$  is the K.E.,  $E_P$  is the P.E. and  $U$  the residual energy stored in the molecular structure of the substance.

$$Q = \Delta E_K + \Delta E_P + \Delta U + W \quad \text{--- (1)}$$

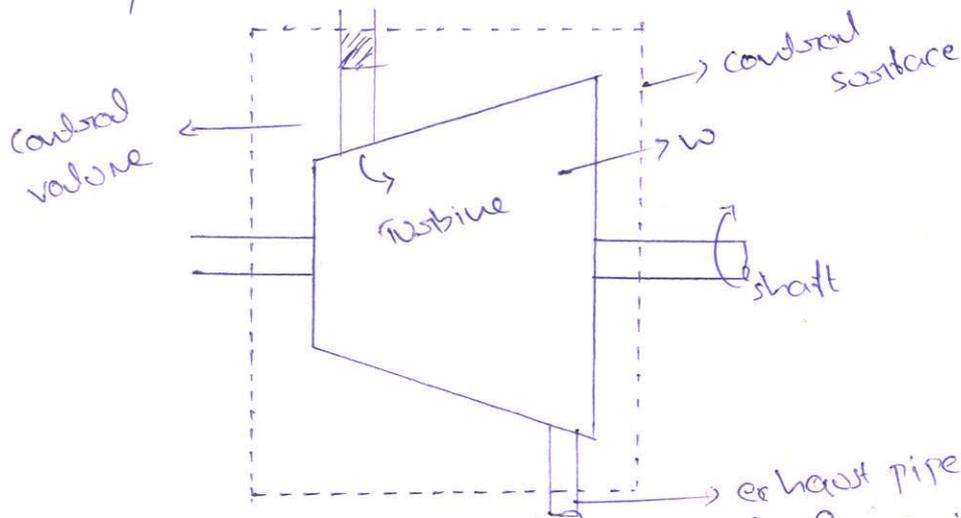
when there is a mass transfer across the system boundary, the system is called an open system. Most of the engineering devices are open systems involving the flow of fluids through them.

eg<sup>n</sup> (1) refers to a system having a particular mass of substance and it is free to move from place to place. Consider a steam turbine in which steam enters at a high pressure, does work upon the turbine rotor, and then leaves the turbine at low pressure through the exhaust pipe.

If a certain mass of steam is considered as the thermodynamic system, then the energy equation becomes

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

and in order to analyze the expansion process in turbine the moving [substance] system is to be followed as it travels through the turbine, taking into account the work and heat interactions all the way through. This method of analysis is similar to that of Lagrange in fluid mechanics.



Although the system approach is quite valid, there is another approach which is found to be highly convenient. Instead of concentrating attention upon a certain quantity of fluid, which constitutes a moving system in flow processes, attention is focused upon a certain fixed region in space called a "control volume" through the moving substance flows. This is similar to the analysis of Euler in fluid mechanics.

To distinguish the two concepts, it may be noted that while the system boundary usually changes shape, position and orientation relative to the observer, the control volume boundary remains fixed and altered. Again while matter usually crosses the control volume boundary, no such flow occurs across the system boundary.

The broken line represents the surface of the control volume which is known as the control surface. This is the same as the system boundary of the open system. The method of analysis to inspect the control surface and account for all energy quantities transferred through this surface. Since there is mass transfer across the control surface, a mass balance also has to be made. Sections (1) and (2) allow mass transfers to take place, and  $\dot{q}$  and  $\dot{w}$  are the heat and work interactions respectively.

Steady flow process - As a fluid flows through a certain control volume, its thermodynamic properties may vary along the space coordinates as well as with time. If the rates of flow of mass and ~~[energy]~~ energy through the control surface change with time, the mass and energy within the control volume also would change with time. Steady flow means that the rates of flow of mass and energy across the control surface are constant.

In most engineering devices, there is a constant rate of flow of mass and energy through the control surface, and the control volume in course of time attains a steady state. At the steady state of a system, any thermodynamic property will have a fixed value at a particular location and will not alter with time. Thermodynamic

properties may vary along space coordinates, but do not vary with time. "steady state" means that the state is steady or invariant with time.

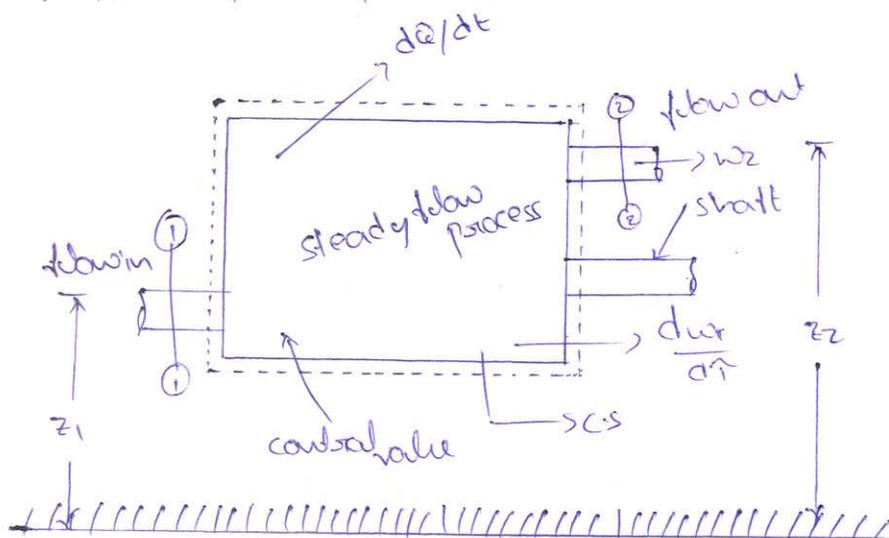
\* Mass balance and energy balance in a simple steady flow process

A steady flow system has been shown in which, one stream of fluid enters and another stream leaves the control volume. There is no accumulation of mass or energy within the control volume, and the properties at any location within the control volume are steady with time. Sections 1-1 and 2-2 indicate respectively the entrance and exit of the fluid across the control surface. The following quantities are defined with reference as shown in figure.

$A_1, A_2 \rightarrow$  cross-section of stream,  $m^2$

$w_1, w_2 \rightarrow$  mass flow rate,  $kg/s$

$P_1, P_2 \rightarrow$  pressure, absolute,  $N/m^2$



$v_1, v_2$  - specific volume,  $m^3/kg$ .

$u_1, u_2$  - specific internal energy,  $J/kg$

$V_1, V_2$  - velocity,  $m/s$

$z_1, z_2$  - elevation above an arbitrary datum,  $m$ .

$\frac{dQ}{dt}$  - net rate of heat transfer through the control surface,  $J/s$

$\frac{dW_x}{dt}$  - net rate of work transfer through the control surface,  $J/s$

Exclusive of work done at sections 1 and 2 in transferring the fluids through the control surface.

$\tau$  - time,  $s$

Subscripts 1 and 2 refer to the inlet and exit sections.

Mass balance

By the conservation of mass, if there is no accumulation of mass within the control volume, the mass flow rate entering must equal the mass flow rate leaving, or

$$w_1 = w_2$$

$$\frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2}$$

This equation is known as the equation of continuity.

## Energy balance

In a flow process, the work transfer may be of two types: the external work and the flow work. The external work refers to all the work transfer across the control surface other than that due to normal fluid forces. In engineering thermodynamics the only kinds of external work of importance are shear work and electrical work. In the only external work occurs in the form of shaft work " $w_x$ ". The flow work as discussed in sec. is the displacement work done by the fluid of mass  $dm_1$  at the inlet section 1 and that of mass  $dm_2$  at the exit section 2, which are  $(-p_1 v_1 dm_1)$  and  $(+p_2 v_2 dm_2)$  respectively. Therefore the total work transfer is given by

$$W = w_x - p_1 v_1 dm_1 + p_2 v_2 dm_2$$

In the rate form,

$$\frac{dW}{dt} = \frac{dw_x}{dt} - p_1 v_1 \frac{dm_1}{dt} + p_2 v_2 \frac{dm_2}{dt}$$

or,

$$\frac{dW}{dt} = \frac{dw_x}{dt} - w_1 p_1 v_1 + w_2 p_2 v_2 \quad \text{--- (*)}$$

Since there is no accumulation of energy, by the conservation of energy, the total rate of flow of all energy streams entering the control volume must equal the total rate of flow of all energy streams leaving the control volume. This may be expressed in the following equation.

$$w_{e1} + \frac{dq}{dt} = w_{e2} + \frac{dW}{dt}$$

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Substituting for  $\frac{dw}{dr}$  from eqn (2)

$$w_1 e_1 + \frac{dq}{dr} = w_2 e_2 + \frac{dq}{dr} - w_1 p_1 v_1 + w_2 p_2 v_2$$

$$\therefore w_1 e_1 + w_1 p_1 v_1 + \frac{dq}{dr} = w_2 e_2 + w_2 p_2 v_2 + \frac{dw_r}{dr} \quad \text{--- (3)}$$

where  $e_1$  and  $e_2$  refer to the energy carried into or out of control volume with unit mass of fluid.

The specific energy  $e$  is given by

$$e = e_k + e_p + u = \frac{v^2}{2} + z g + u \quad \text{--- (4)}$$

Substituting these eqn for  $e$  in eqn (3)

$$w_1 \left[ \frac{v_1^2}{2} + z_1 g + u_1 \right] + w_1 p_1 v_1 + \frac{dq}{dr} \\ = w_2 \left[ \frac{v_2^2}{2} + z_2 g + u_2 \right] + w_2 p_2 v_2 + \frac{dw_r}{dr}$$

or,

$$= w_1 \left[ h_1 + \frac{v_1^2}{2} + z_1 g \right] + \frac{dq}{dr}$$

$$= w_2 \left[ h_2 + \frac{v_2^2}{2} + z_2 g \right] + \frac{dw_r}{dr} \quad \text{--- (5)}$$

where  $h = u + p v$

and  $\therefore w_1 = w_2$ , let  $w = w_1 = w_2 = \frac{dM}{dr}$  -

dividing equation (5) by  $\frac{dM}{dr}$

$$h_1 + \frac{v_1^2}{2} + z_1 g + \frac{dq}{dM} = h_2 + \frac{v_2^2}{2} + z_2 g + \frac{dw_r}{dM} \quad \text{--- (6)}$$

Equation (5) or (6) are known as steady flow energy equations [S.F.E.E] for a single stream of fluid entering and a single stream of fluid leaving the control volume. all the terms in equation (6) represent energy flow per unit mass of fluid (J/kg), whereas the terms in equation (5) represent energy flow per unit time (J/s). the basis of energy flow per unit mass is usually more convenient when only a single stream of fluid enters and leaves a control volume. when more than one fluid stream is involved the basis of energy flow per unit time is more convenient.

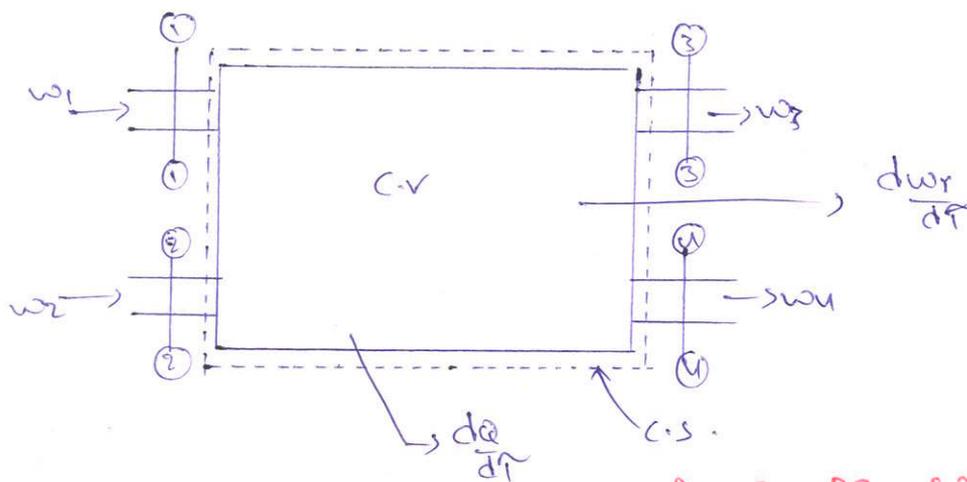
Eq<sup>n</sup> (6) can be written in the following form,

$$Q - W_x = (h_2 - h_1) + \frac{\bar{v}_2^2 - \bar{v}_1^2}{2} + g(z_2 - z_1) \quad \text{--- (6)}$$

where  $Q$  and  $W_x$  refer to energy transferred per unit mass. In the differential form, the SFEE becomes.

$$dq - dw_x = dh + \bar{v}d\bar{v} + gdz$$

When more than one stream of fluid enters or leaves the control volume in below figure, the mass balance and energy balance for steady flow are given as follows.



Mass balance

$$w_1 + w_2 = w_3 + w_4 \quad - (6)$$

$$\frac{A_1 V_1}{\rho_1} + \frac{A_2 V_2}{\rho_2} = \frac{A_3 V_3}{\rho_3} + \frac{A_4 V_4}{\rho_4} \quad - (7)$$

Energy balance,

$$= w_1 \left[ h_1 + \frac{V_1^2}{2} + z_1 g \right] + w_2 \left[ h_2 + \frac{V_2^2}{2} + z_2 g \right] + \frac{dQ}{dt}$$

$$= w_3 \left[ h_3 + \frac{V_3^2}{2} + z_3 g \right] + w_4 \left[ h_4 + \frac{V_4^2}{2} + z_4 g \right] + \frac{dW_x}{dt} \quad - (8)$$

The steady flow energy equation applies to a wide variety of process like pipe line flows, heat transfer processes, mechanical power generation in engines and turbines, combustion processes and flows through nozzles and diffusers. In certain problems, some of the terms in steady flow energy equation may be negligible or zero. But it is best to write the full equation first and then eliminate the terms which are unnecessary.

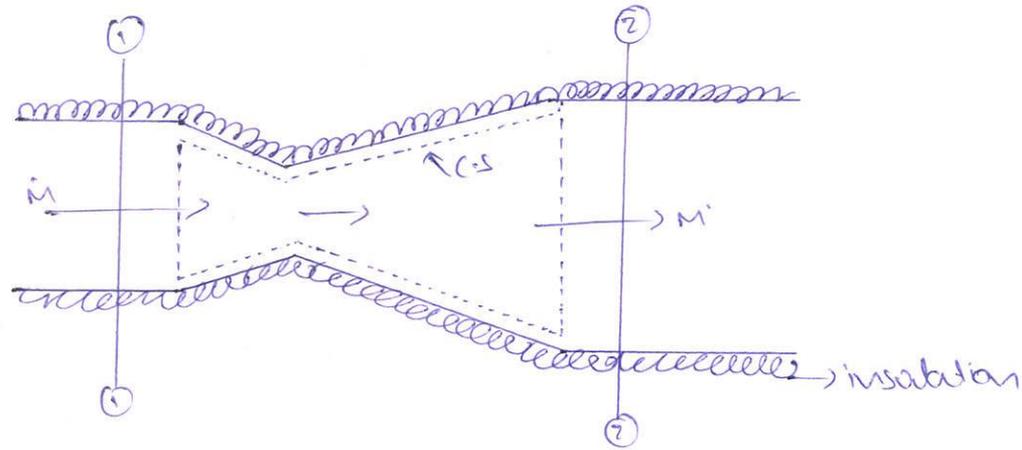
Examples of steady flow process

The following examples illustrate the applications of the steady flow energy equation in some of the engineering systems.

Nozzle and diffuser - A nozzle is a device which increases the velocity or K.E of a fluid at the expense of its pressure drop, whereas a diffuser increases the pressure of a fluid at the expense of its K.E. In figure shows a nozzle which

is insulated. The steady flow energy equation of the control surface gives

$$h_1 + \frac{v_1^2}{2} + z_1 g + \frac{dq}{dm} = h_2 + \frac{v_2^2}{2} + z_2 g + \frac{dw_x}{dm}$$



steady flow process involving two fluid streams at the inlet and exit of the control volume.

Here  $\frac{dq}{dm} = 0$ ,  $\frac{dw_x}{dm} = 0$  and the change in potential energy is zero. The equation reduces to

$$h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2} \quad \text{--- (9)}$$

The continuity equation gives

$$w = \frac{A_1 v_1}{v_1} = \frac{A_2 v_2}{v_2} \quad \text{--- (10)}$$

when the inlet velocity or the "velocity of approach"  $v_1$  is small compared to the exit velocity  $v_2$ , eqn (9) becomes

$$h_1 = h_2 + \frac{v_2^2}{2}$$

$$v_2 = \sqrt{2(h_1 - h_2) M_1 S}$$

where  $(h_1 - h_2)$  is in J/kg

Equations (9) and (10) hold good for a diffuser as well.

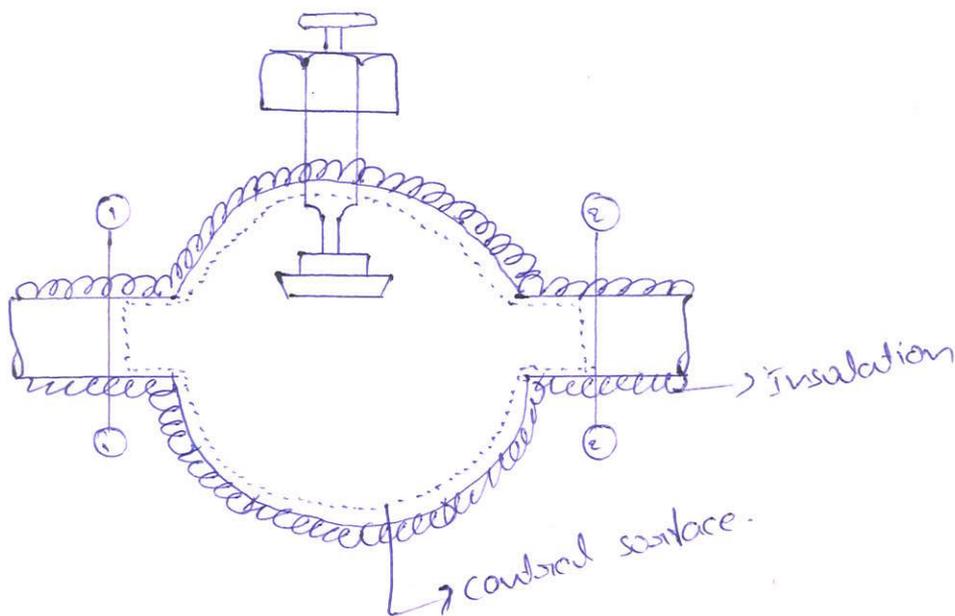
Throttling device when a fluid flows through a constricted passage, like a partially valve, an orifice, or a porous plug there is an appreciable drop in pressure, and the flow is said to be throttled. In below figure shows the process of throttling by a partially opened valve on a fluid flowing in an insulated pipe. In the steady flow energy equation

$$\frac{dq}{dm} = 0, \frac{dw}{dm} = 0$$

and the changes in P.E are very small and ignored.

Thus, the S.F.E.E reduces to

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$



flow through a valve.

often the pipe velocities in throttling are so low that the K.E terms are also negligible. so

$$h_1 = h_2$$

or the enthalpy of the fluid before throttling is equal to the enthalpy of the fluid after throttling.

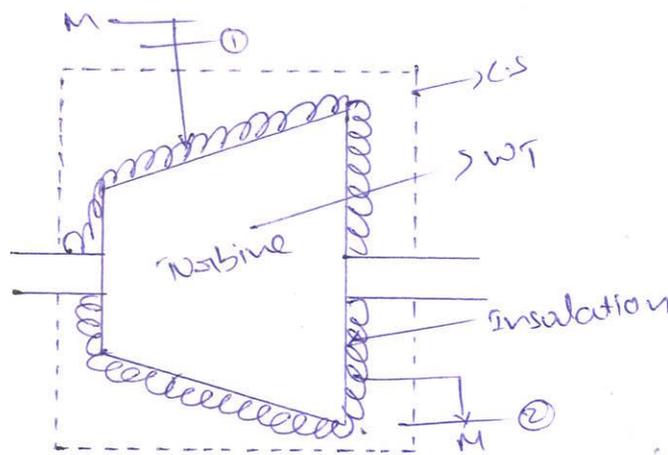
### Turbine and compressor :-

Turbines and engines give positive power output whereas compressors and pumps require power input.

for a turbine which is well insulated, the flow velocities are often small and the K.E terms can be neglected. the S.F.E.E then becomes

$$h_1 = h_2 + \frac{dw_r}{dM}$$

$$\frac{w_r}{M} = (h_1 - h_2)$$



flow through a turbine.

It is seen that work is done by the fluid at the expense of its enthalpy. similarly for an adiabatic pump or compressor, work is done upon the fluid and  $w_i$  is

negative. so the S.F.E.E becomes.

$$h_1 = h_2 - \frac{w_r}{M}$$

$$\frac{w_r}{M} = h_2 - h_1$$

The enthalpy of the fluid increases by the amount of work input.  
∴



(1) A new temperature scale in degrees N is to be defined. The boiling and freezing points on this scale are  $400^{\circ}N$  and  $100^{\circ}N$  respectively.

(a) correlate this with

(i) centigrade scale and

(ii) Fahrenheit scale

(b) what will be the reading on new scale corresponding to  $60^{\circ}C$ .

Ans

(a)  
(i)

The temperature corresponding to any length ' $t$ ' of fluid thermometer is

$$t = at + b \rightarrow (1)$$

where 'a' and 'b' are constants for a centigrade thermometer. Boiling and freezing points are  $100^{\circ}C$  and  $0^{\circ}C$ .

$$0 = a l_1 + b \rightarrow (2)$$

$$100 = a l_2 + b \rightarrow (3)$$

Subtracting equation (3) from (2), we get,

$$100 = a (l_2 - l_1)$$

$$a = \frac{100}{l_2 - l_1}$$

from equation (2)

$$b = -a l_1 = \frac{-100 l_1}{l_2 - l_1}$$

$$\therefore t^{\circ}\text{C} = \frac{100l}{l_2 - l_1} - \frac{100l_1}{l_2 - l_1}$$

$$t^{\circ}\text{C} = 100 \left( \frac{l - l_1}{l_2 - l_1} \right) = \left( \frac{100}{l_2 - l_1} \right) (l - l_1)$$

For the given temperature scale, the boiling and freezing points are  $400^{\circ}\text{N}$  and  $100^{\circ}\text{N}$  respectively.

we have

$$t = al + b$$

$$\therefore 100 = al + b \rightarrow \textcircled{4}$$

$$\therefore 400 = al_2 + b \rightarrow \textcircled{5}$$

Subtracting equations  $\textcircled{4}$  &  $\textcircled{5}$

$$300 = a(l_2 - l_1)$$

$$a = \frac{300}{l_2 - l_1}$$

From equation  $\textcircled{4}$

$$b = 100 - al_1$$

$$b = 100 - \frac{300l_1}{l_2 - l_1}$$

Now substituting the values of  $a$  and

$b$  in equation  $\textcircled{1}$ , then we get.

$$t^{\circ}\text{N} = \frac{300}{l_2 - l_1} l + 100 - \frac{300l_1}{l_2 - l_1}$$

$$t^{\circ}\text{N} = \left( \frac{300}{l_2 - l_1} \right) (l - l_1) + 100 \rightarrow \textcircled{6}$$

$$t^{\circ}\text{N} = 3 \left( \frac{100}{l_2 - l_1} \right) (l - l_1) + 100$$

$$t^{\circ}\text{N} = 3t^{\circ}\text{C} + 100$$

(ii) For a Fahrenheit scale, the boiling and freezing points are  $212^{\circ}\text{F}$  and  $32^{\circ}\text{F}$  respectively

we have

$$t = at + b$$

$$32 = al_1 + b \rightarrow \textcircled{7}$$

$$212 = al_2 + b \rightarrow \textcircled{8}$$

subtracting eqns  $\textcircled{7}$  &  $\textcircled{8}$

$$180 = a(l_2 - l_1)$$

$$a = \frac{180}{l_2 - l_1}$$

From eqn  $\textcircled{7}$

$$b = 32 - al_1$$

$$b = 32 - \frac{180l_1}{l_2 - l_1}$$

Substituting values of  $a$  and  $b$  in  $\textcircled{1}$  we

get that

$$\begin{aligned} t^{\circ}\text{F} &= \frac{180}{l_2 - l_1} l + 32 - \frac{180l_1}{l_2 - l_1} \\ &= 180 \left( \frac{l - l_1}{l_2 - l_1} \right) + 32 \rightarrow \textcircled{9} \end{aligned}$$

we have

$$\begin{aligned} t^{\circ}\text{N} &= 300 \left( \frac{l - l_1}{l_2 - l_1} \right) + 100 \\ &= 300 \left( \frac{t^{\circ}\text{F} - 32}{180} \right) + 100 \end{aligned}$$

$$t^{\circ}\text{N} = \frac{5}{9} (t^{\circ}\text{F} - 32) + 100$$



Ans

Given that

A closed system undergoes a thermodynamic cycle.

$$\text{i.e.; } \int Q = \int W$$

Algebraic sum of heat transfers

= Algebraic sum of work transfer

consider process 1-2 :-

Given that,

$$Q_{12} = 20,000 \text{ kJ/min}$$

$$W_{12} = 0$$

According to first law of TD's for a closed system

$$Q_{12} = \Delta E_{12} + W_{12}$$

$$20,000 = \Delta E_{12} + 0$$

$$\Delta E_{12} = 20,000 \text{ kJ/min}$$

consider process 2-3 :-

Given that

$$Q_{23} = -10,000 \text{ kJ/min}$$

(Negative signs mean heat rejected from system)

$$W_{23} = 30,000 \text{ kJ/min}$$

According to 1st law of thermodynamics,

$$Q_{23} = \Delta E_{23} + W_{23}$$

$$-10,000 = \Delta E_{23} + 30,000$$

$$\Delta E_{23} = -40,000 \text{ kJ/min}$$

consider process 3-4 :-

$$\text{Given } Q_{3-4} = 0$$

$$W_{3-4} = 20,000 \text{ kJ/min}$$

According to 1<sup>st</sup> law of thermodynamics

$$Q_{3-4} = \Delta E_{3-4} + W_{3-4}$$

$$0 = \Delta E_{3-4} + 20,000$$

$$\Delta E_{3-4} = -20,000 \text{ kJ/min}$$

[Negative sign indicates internal energy is decreased]

consider process 4-1 :-

$$\text{Given } Q_{4-1} = 15,000 \text{ kJ/min}$$

$$W_{4-1} = -25,000 \text{ kJ/min}$$

[Negative sign indicates work done upon the system]

According to 1<sup>st</sup> law of thermodynamics,

$$Q_{4-1} = \Delta E_{4-1} + W_{4-1}$$

$$15,000 = \Delta E_{4-1} + (-25,000)$$

$$\Delta E_{4-1} = 40,000 \text{ kJ/min}$$

$$\Sigma Q = 20,000 - 10,000 + 0 + 15,000$$

$$\Sigma Q = 25,000 \text{ kJ/min}$$

$$\Sigma W = 0 + 30,000 + 20,000 - 25,000$$

$$\Sigma W = 25,000 \text{ kJ/min}$$

It is clearly observed that

$$\Sigma Q = \Sigma W$$

$$\text{i.e.; } \Sigma Q = \Sigma W$$

The given data in tabular form is consistent with first law of thermodynamics.

∴ Net work output (in kilo watt)

$$\begin{aligned}W_{\text{net}} &= 0 + 30,000 + 20,000 - 25,000 = 25,000 \text{ kJ/min} \\ &= \frac{25,000}{60} \text{ kJ/sec} \\ &= 416.66 \text{ kW}\end{aligned}$$

Net change of internal energy of a closed thermodynamic system.

$$\begin{aligned}\Delta E_{1-2-3-4} &= \Delta E_{12} + \Delta E_{23} + \Delta E_{34} + \Delta E_{41} \\ &= 20,000 - 4,000 - 20,000 + 40,000 \\ &= 0\end{aligned}$$

It is also clearly observed that, the net change of internal energy is zero, it is consistent with 1<sup>st</sup> law of thermodynamics.



3) A fluid is contained in a cylinder by a spring loaded, friction-less piston so that the pressure in the fluid is linear function of volume ( $P = a + bv$ ). The internal energy of the fluid in kJ is given by the expression  $u = 32 + 3pv$ , where  $p$  is in kPa and  $v$  is in  $m^3$ . The initial and final pressures are 150 kPa and 350 kPa and the corresponding volumes are  $0.02 m^3$  and  $0.05 m^3$ . Make calculations for the direction & magnitude of work & heat interactions.

Ans:

Given that

$$P = a + bv$$

$$u = 32 + 3pv$$

$$\text{Initial pressure} = 150 \text{ kPa} = P_i$$

$$\text{Initial volume}, v_i = 0.02 \text{ m}^3$$

$$\text{Final Pressure } P_f = 350 \text{ kPa}$$

$$\text{Final volume}, V_f = 0.05 \text{ m}^3$$

Change in internal energy of the fluid during the process = ?

$$u_i = 32 + 3P_i v_i$$

$$u_f = 32 + 3P_f v_f$$

$$u_f - u_i = 3(P_f v_f - P_i v_i)$$

$$= 3(350 \times 0.05 - 150 \times 0.02)$$

$$u_f - u_i = 43.5 \text{ kJ}$$

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On solving the above two equations, we get,

$$a = 10.667 \text{ kN/m}^2$$

$$b = 6666.667 \text{ kN/m}^2$$

Now, work transfer involved during the process

$$\begin{aligned} W_{1-2} &= \int_{v_i}^{v_f} p \, dv \\ &= \int_{v_i}^{v_f} (a + bv) \, dv \\ &= \int_{v_i}^{v_f} a \, dv + \int_{v_i}^{v_f} bv \, dv \\ &= a(v_f - v_i) + b \frac{v_f^2 - v_i^2}{2} \\ &= 14.5 \text{ kJ} \end{aligned}$$

$\therefore$  work is done by the system, the magnitude being 14.5 kJ

Heat transfer involved

$$\begin{aligned} Q_{1-2} &= u_f - u_i + W_{1-2} \\ &= 43.5 + 14.5 \\ &= 58 \text{ kJ} \end{aligned}$$

Heat is transferred into the system, magnitude being 58 kJ

④ A system undergoes a cycle composed of four (transfers) processes. The heat transfers in each process are:  $400 \text{ kJ}$ ,  $-365 \text{ kJ}$ ,  $-200 \text{ kJ}$ , and  $250 \text{ kJ}$ . The respective work transfers are  $140 \text{ kJ}$ ,  $0$ ,  $-55 \text{ kJ}$  and  $0$ . Is the data consistent with first law of thermodynamics?

Ans

Given that

A cycle is composed of 4 processes.

Let the cycle be 1-2-3-4-1 and the processes be

1-2, 2-3, 3-4, 4-1.

For process 1-2 :-

Heat interaction  $Q_{1-2} = 400 \text{ kJ}$

work transfer  $W_{1-2} = 140 \text{ kJ}$

For process 2-3 :-

Heat interaction,  $Q_{2-3} = -365 \text{ kJ}$

work transfer,  $W_{2-3} = 0 \text{ kJ}$

For process 3-4 :-

Heat interaction,  $Q_{3-4} = -200 \text{ kJ}$

work transfer,  $W_{3-4} = -55 \text{ kJ}$

For process 4-1 :-

Heat transfer,  $Q_{4-1} = 250 \text{ kJ}$

work transfer,  $W_{4-1} = 0 \text{ kJ}$

According to First law of thermodynamics,

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

$$w_{1-2} + w_{2-3} + w_{3-4} + w_{4-1} = Q_{1-2} + Q_{2-3} + Q_{3-4} + Q_{4-1}$$

$$140 + 0 + (-55) + 0 = 400 - 365 - 200 + 250$$

$$85 = 85$$

i.e; Net ~~to~~ heat interaction of the cycle is equal to the net work transfer of the cycle.

∴ The given data is consistent with first law of thermodynamics.

— o —

(5) A gas undergoes a thermodynamic cycle consisting of three processes beginning at an initial state where  $P_1 = 1 \text{ bar}$ ,  $V_1 = 1.5 \text{ m}^3$  and  $U_1 = 512 \text{ kJ}$ . The processes are as follows.

(a) Process 1-2: compression with  $PV = \text{constant}$  to  $P_2 = 2 \text{ bar}$ ,  $U_2 = 690 \text{ kJ}$ .

(b) Process 2-3:  $w_{2-3} = 0$ ,  $Q_{2-3} = -150 \text{ kJ}$ , and

(c) Process 3-1:  $w_{3-1} = 50 \text{ kJ}$

Neglecting KE & PE changes, determine the heat interaction  $Q_{1-2}$  &  $Q_{3-1}$

Ans

Given that,

Initial pressure = 1 bar

Initial volume = 1.5 m<sup>3</sup>

Initial internal energy = 512 kJ

Process 1-2:

Compression,  $PV = \text{constant}$ ,  $P_2 = 2 \text{ bar}$ ,  $U_2 = 690 \text{ kJ}$

Process 2-3: ~~P=const~~

$$W_{2-3} = 0, \quad Q_{2-3} = -150 \text{ kJ}$$

Process 3-1:-

$$W_{3-1} = 50 \text{ kJ}$$

To find heat interactions  $Q_{1-2}$  &  $Q_{3-1} = ?$

According to first law of thermodynamics for a process.

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

For Process 1-2

~~(compression with  $PV = \text{const}$ )~~

$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

$$U_2 - U_1 = 690 - 512$$

$$U_2 - U_1 = 178 \text{ kJ}$$

$$PV = \text{constant}$$

$$P_1 V_1 = P_2 V_2$$

$$V_2 = \frac{P_1 V_1}{P_2} = \frac{1 \times 1.5}{2} = 0.75 \text{ m}^3$$

$$W_{1-2} = P_1 V_1 \ln \left( \frac{V_2}{V_1} \right)$$

$$= 1 \times 10^5 \times 1.5 \ln \left( \frac{0.75}{1.5} \right)$$

$$= -103.97 \text{ kJ}$$

$$Q_{1-2} = 178 - 103.97$$

$$Q_{1-2} = 74.03 \text{ kJ}$$

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For process 2-3

$$w_{2-3} = 0$$

$$Q_{2-3} = \Delta U$$

$$Q_{2-3} = U_3 - U_2$$

$$-150 = U_3 - 690$$

$$U_3 = 540 \text{ kJ}$$

For process 3-1

$$\begin{aligned} \Delta U &= U_1 - U_3 \\ &= 512 - 540 \end{aligned}$$

$$= -28 \text{ kJ}$$

$$\Delta U = -28 \text{ kJ}$$

$$Q_{3-1} = \Delta U + w_{3-1}$$

$$= -28 + 50$$

$$= 22 \text{ kJ}$$

$$\boxed{Q_{3-1} = 22 \text{ kJ}}$$

→ 0