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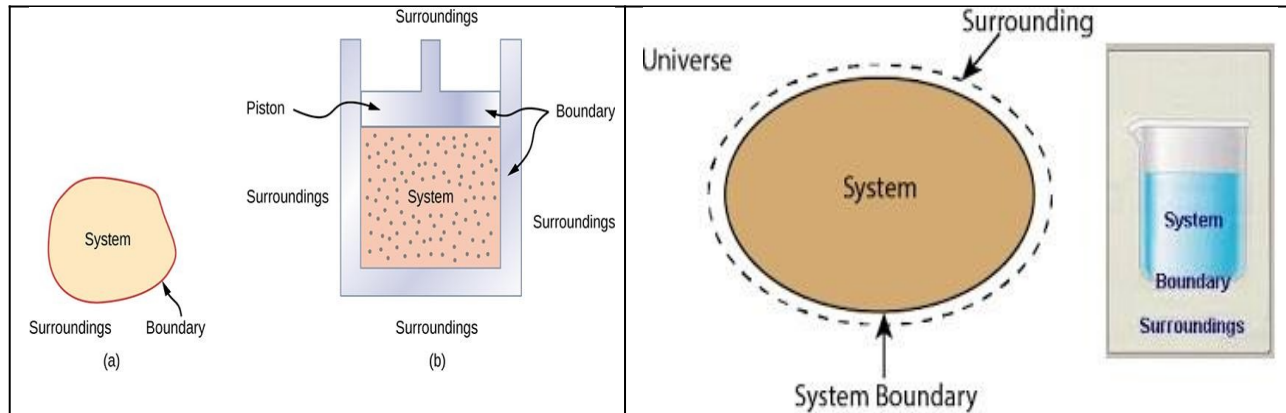
Department of Mechanical Engineering
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Subject: Thermodynamics
Code: 23ME305

UNIT I

System: A thermodynamic system is defined as a quantity of matter or a region in space which is selected for the study.

Surroundings: The mass or region outside the system is called surroundings.

Boundary: The real or imaginary surfaces which separates the system and surroundings is called boundary.



Types of thermodynamic system

On the basis of mass and energy transfer the thermodynamic system is divided into three types.

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

Closed system: A system in which the transfer of energy but not mass can take place across the boundary is called closed system. The mass inside the closed system remains constant.

For example: Boiling of water in a closed vessel. Since the water is boiled in a closed vessel so the mass of water cannot escape out of the boundary of the system but heat energy continuously enters and leaves the boundary of the vessel. It is an example of closed system.

Open system: A system in which the transfer of both mass and energy takes place is called an open system. This system is also known as control volume.

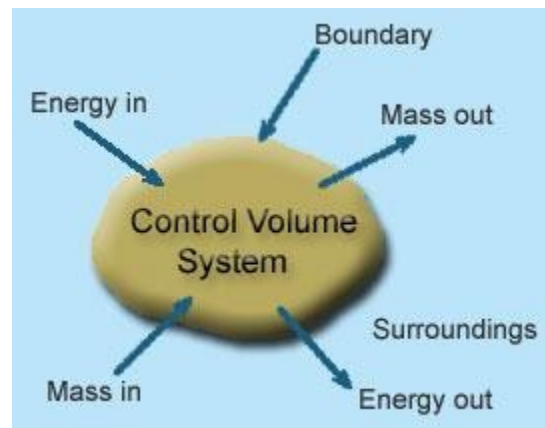
For example: Boiling of water in an open vessel is an example of open system because the water and heat energy both enter and leave the boundary of the vessel.

Isolated system: A system in which the transfer of mass and energy cannot take place is called an isolated system.

For example: Tea present in a thermos flask. In this the heat and the mass of the tea cannot cross the boundary of the thermos flask. Hence the thermos flask is an isolated system.

Control Volume:

- Its a system of fixed volume.
- This type of system is usually referred to as "open system" or a "control volume"
- Mass transfer can take place across a control volume.
- Energy transfer may also occur into or out of the system.
- Control Surface- Its the boundary of a control volume across which the transfer of both mass and energy takes place.
- The mass of a control volume (open system) may or may not be fixed.
- When the net influx of mass across the control surface equals zero then the mass of the system is fixed and vice-versa.
- The identity of mass in a control volume always changes unlike the case for a control mass system (closed system).
- Most of the engineering devices, in general, represent an open system or control volume.



Example: **Heat exchanger** - Fluid enters and leaves the system continuously with the transfer of heat across the system boundary. **Pump** - A continuous flow of fluid takes place through the system with a transfer of mechanical energy from the surroundings to the system

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Microscopic Approach:

- The approach considers that the system is made up of a very large number of discrete particles known as molecules. These molecules have different velocities and energies. The values of these energies are constantly changing with time. This approach to

thermodynamics, which is concerned directly with the structure of the matter, is known as statistical thermodynamics.

- The behavior of the system is found by using statistical methods, as the number of molecules is very large. So advanced statistical and mathematical methods are needed to explain the changes in the system.
- The properties like velocity, momentum, impulse, kinetic energy and instruments cannot easily measure force of impact etc. that describe the molecule.
- Large numbers of variables are needed to describe a system. So the approach is complicated.

Macroscopic Approach:

- In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level. In other words this approach to thermodynamics is concerned with gross or overall behavior. This is known as classical thermodynamics.
- The analysis of macroscopic system requires simple mathematical formula.
- The value of the properties of the system are their average values. For examples consider a sample of gas in a closed container. The pressure of the gas is the average value of the pressure exerted by millions of individual molecules.
- In order to describe a system only a few properties are needed.

S.No	Microscopic Approach	Macroscopic Approach
01	In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level	The matter is considered to be comprised of a large number of tiny particles known as molecules, which moves randomly in chaotic fashion. The effect of molecular motion is considered.
02	Analysis is concerned with overall behavior of the system.	The Knowledge of the structure of matter is essential in analyzing the behavior of the system
03	This approach is used in the study of classical thermodynamics.	This approach is used in the study of statistical thermodynamics.
04	A few properties are required to describe the system.	Large numbers of variables are required to describe the system.
05	The properties like pressure, temperature, etc. needed to describe the system, can be easily measured.	The properties like velocity, momentum, kinetic energy, etc. needed to describe the system, cannot be measured easily.
06	The properties of the system are their average values.	The properties are defined for each molecule individually.
07	This approach requires simple	No. of molecules are very large so it requires

	mathematical formulas for analyzing the system.	advanced statistical and mathematical method to explain any change in the system.
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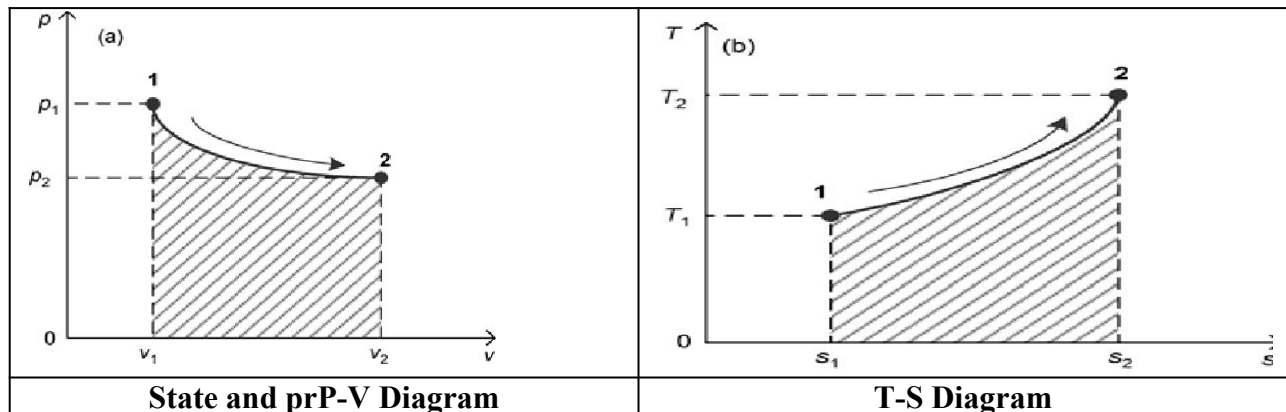
Thermodynamic Equilibrium:

A thermodynamic system is said to exist in a state of thermodynamic equilibrium when no change in any macroscopic property is registered if the system is isolated from its surroundings. An isolated system always reaches in the course of time a state of thermodynamic equilibrium and can never depart from it spontaneously. Therefore, there can be no spontaneous change in any macroscopic property if the system exists in an equilibrium state. A thermodynamic system will be in a state of thermodynamic equilibrium if the system is the state of Mechanical equilibrium, Chemical equilibrium and Thermal equilibrium.

- **Mechanical equilibrium:** The criteria for Mechanical equilibrium are the equality of pressures.
- **Chemical equilibrium:** The criteria for Chemical equilibrium are the equality of chemical potentials.
- **Thermal equilibrium:** The criterion for Thermal equilibrium is the equality of temperatures.

State: The thermodynamic state of a system is defined by specifying values of a set of measurable properties sufficient to determine all other properties. For fluid systems, typical properties are pressure, volume and temperature. More complex systems may require the specification of more unusual properties. As an example, the state of an electric battery requires the specification of the amount of electric charge it contains.

Property: Properties may be extensive or intensive.



Intensive properties: The properties which are independent of the mass of the system. For example: Temperature, pressure and density are the intensive properties.

Extensive properties: The properties which depend on the mass of the system are called extensive properties. For example: Total mass, total volume and total momentum.

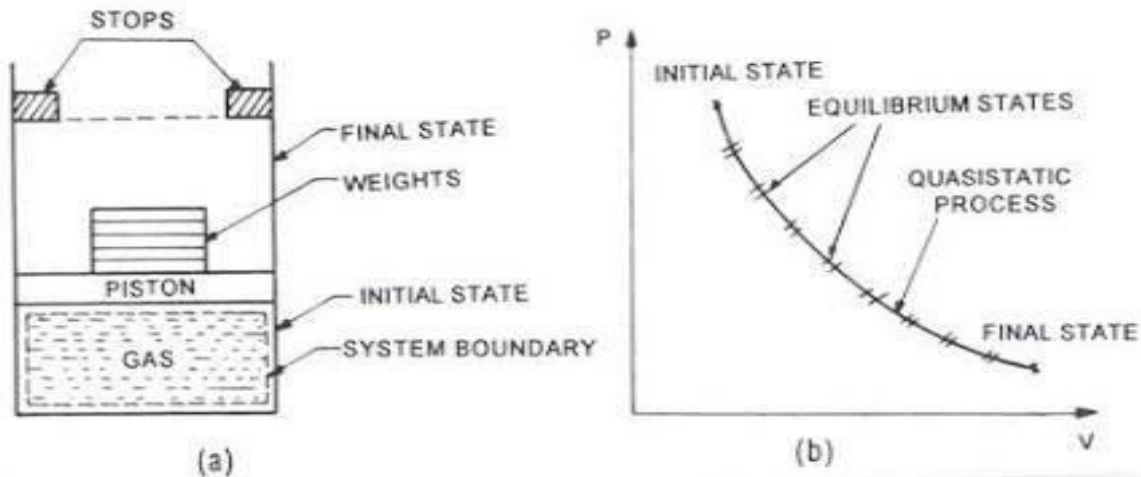
Process: When the system undergoes change from one thermodynamic state to final state due change in properties like temperature, pressure, volume etc, the system is said to have undergone thermodynamic process. Various types of thermodynamic processes are: isothermal process, adiabatic process, isochoric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

Cycle: Thermodynamic cycle refers to any closed system that undergoes various changes due to temperature, pressure, and volume, however, its final and initial state are equal. This cycle is important as it allows for the continuous process of a moving piston seen in heat engines and the expansion/compression of the working fluid in refrigerators, for example. Without the cyclical process, a car wouldn't be able to continuously move when fuel is added, or a refrigerator would not be able to stay cold.

Visually, any thermodynamic cycle will appear as a closed loop on a pressure volume diagram. Examples: Otto cycle, Diesel Cycle, Brayton Cycle etc.

Reversibility: Reversibility, in thermodynamics, a characteristic of certain processes (changes of a system from an initial state to a final state spontaneously or as a result of interactions with other systems) that can be reversed, and the system restored to its initial state, without leaving net effects in any of the systems involved. An example of a reversible process would be a single swing of a frictionless pendulum from one of its extreme positions to the other. The swing of a real pendulum is irreversible because a small amount of the mechanical energy of the pendulum would be expended in performing work against frictional forces, and restoration of the pendulum to its exact starting position would require the supply of an equivalent amount of energy from a second system, such as a compressed spring in which an irreversible change of state would occur.

Quasi static process: When a process is processing in such a way that system will be remained infinitesimally close with equilibrium state at each time, such process will be termed as quasi static process or quasi equilibrium process. In simple words, we can say that if system is going under a thermodynamic process through succession of thermodynamic states and each state is equilibrium state then the process will be termed as quasi static process



We will see one example for understanding the quasi static process, but let us consider one simple example for better understanding of quasi static process. If a person is coming down from roof to ground floor with the help of ladder steps then it could be considered as quasi static process. But if he jumps from roof to ground floor then it will not be a quasi static process. Weight placed over the piston is just balancing the force which is exerted in upward direction by gas. If we remove the weight from the piston, system will have unbalanced force and piston will move in upward direction due to force acting over the piston in upward direction by the gas.

Irreversible Process: The irreversible process is also called the natural process because all the processes occurring in nature are irreversible processes. The natural process occurs due to the finite gradient between the two states of the system. For instance, heat flow between two bodies occurs due to the temperature gradient between the two bodies; this is in fact the natural flow of heat. Similarly, water flows from high level to low level, current moves from high potential to low potential, etc.

- In the irreversible process the initial state of the system and surroundings cannot be restored from the final state.
- During the irreversible process the various states of the system on the path of change from initial state to final state are not in equilibrium with each other.
- During the irreversible process the entropy of the system increases decisively and it cannot be reduced back to its initial value.
- The phenomenon of a system undergoing irreversible process is called as irreversibility

Causes of Irreversibility:

Friction: Friction is invariably present in real systems. It causes irreversibility in the process as work done does not show an equivalent rise in the kinetic or potential energy of the system. The fraction of energy wasted due to frictional effects leads to deviation from reversible states.

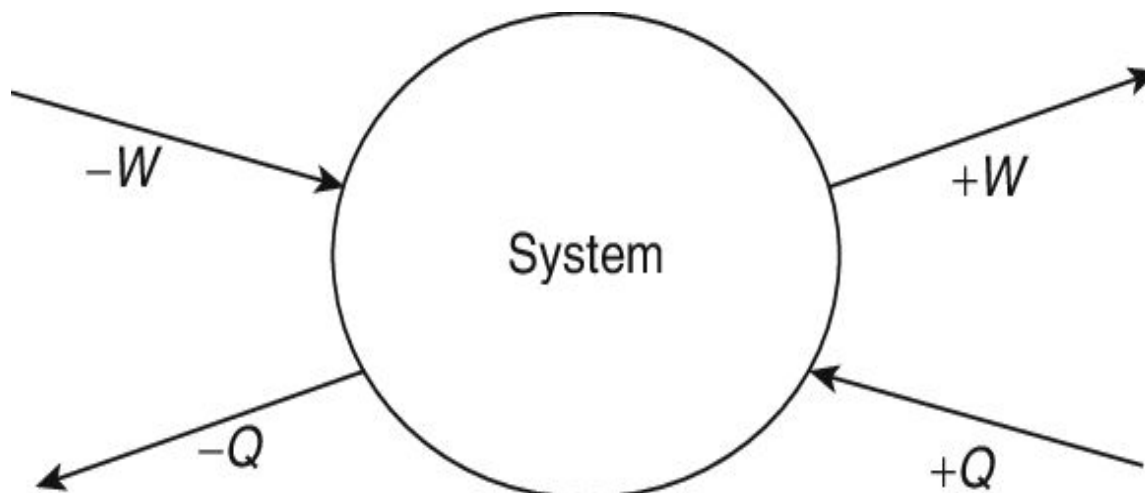
Free expansion: Free expansion refers to the expansion of an unresisted type such as expansion in a vacuum. During this unresisted expansion the work interaction is zero, and without the expense of any work, it is not possible to restore initial states. Thus, free expansion is irreversible.

Heat transfer through a finite temperature difference: Heat transfer occurs only when there exists a temperature difference between bodies undergoing heat transfer. During heat transfer, if heat addition is carried out in a finite number of steps then after every step the new state shall be a non-equilibrium state.

Non equilibrium during the process: Irreversibility's are introduced due to lack of thermodynamic equilibrium during the process. Non-equilibrium may be due to mechanical non-equilibrium, chemical non-equilibrium, thermal non-equilibrium, electrical non-equilibrium, etc. and irreversibility is called mechanical irreversibility, chemical irreversibility, thermal irreversibility, electrical irreversibility respectively. Factors discussed above are also causing non-equilibrium during the process and therefore make process irreversible

Heat: It is the energy in transition between the system and the surroundings by virtue of the difference in temperature. Heat is energy transferred from one system to another solely by reason of a temperature difference between the systems. Heat exists only as it crosses the boundary of a system and the direction of heat transfer is from higher temperature to lower temperature. For thermodynamics sign convention, heat transferred to a system is positive; Heat transferred from a system is negative.

Work: Thermodynamic definition of work: Positive work is done by a system when the sole effect external to the system could be reduced to the rise of a weight. Work done BY the system is positive and work done ON the system is negative.



Types of work interaction:

- Expansion and compression work (displacement work)
- Work of a reversible chemical cell
- Work in stretching of a liquid surface
- Work done on elastic solids
- Work of polarization and magnetization

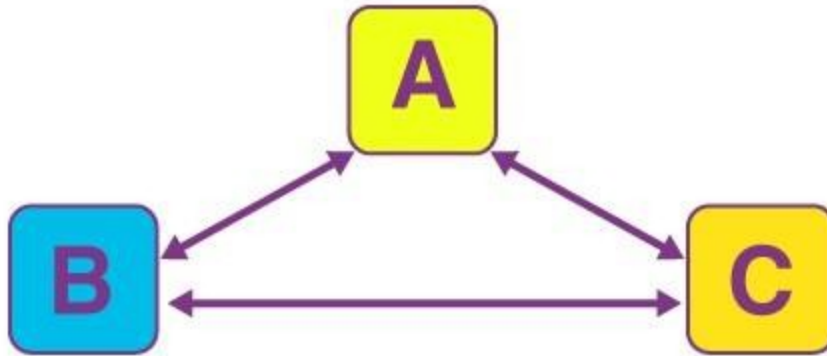
Point and Path functions:

- Point function does not depend on the history (or path) of the system. It only depends on the state of the system.
- Examples of point functions are: temperature, pressure, density, mass, volume, enthalpy, entropy, internal energy etc.
- Path function depends on history of the system (or path by which system arrived at a given state).
- Examples for path functions are work and heat.
- Path functions are not properties of the system, while point functions are properties of the system.
- Change in point function can be obtained by from the initial and final values of the function, whereas path has to define in order to evaluate path functions.

Zeroth Law of Thermodynamics:

The Thermodynamics Zeroth Law states that if two systems are at the same time in thermal equilibrium with a third system, they are in equilibrium with each other. If an object with a higher temperature comes in contact with an object of lower temperature, it will transfer heat to the lower temperature object. The objects will approach the same temperature and in the absence of loss to other objects, they will maintain a single constant temperature. Therefore, thermal equilibrium is attained.

If objects 'A' and 'C' are in thermal equilibrium with 'B', then object 'A' is in thermal equilibrium with object 'C'. Practically this means all three objects are at the same temperature and it forms the basis for comparison of temperatures.



The zeroth law of thermodynamics states that if two thermodynamic systems are each in thermal equilibrium with a third one, then they are in thermal equilibrium with each other.

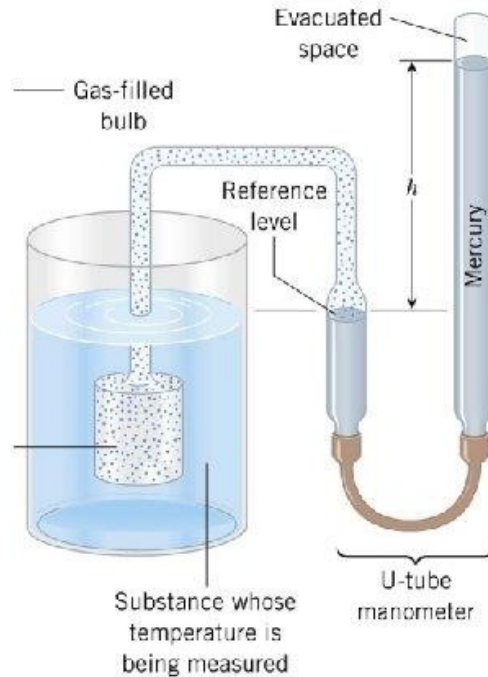
Principles of Thermometry:

Thermometry is the science and practice of temperature measurement. Any measurable change in a thermometric probe (e.g. the dilatation of a liquid in a capillary tube, variation of electrical resistance of a conductor, of refractive index of a transparent material, and so on) can be used to mark temperature levels, that should later be calibrated against an internationally agreed unit if the measure is to be related to other thermodynamic variables. Thermometry is sometimes split in metrological studies in two subfields: contact thermometry and noncontact thermometry. As there can never be complete thermal uniformity at large, thermometry is always associated to a heat transfer problem with some space-time coordinates of measurement, given rise to time-series plots and temperature maps.

Constant Volume gas Thermometer:

When we heat a gas keeping the volume constant, its pressure increases and when we cool the gas its pressure decreases. The relationship between pressure and temperature at constant volume is given by the law of pressure. According to this law, the pressure of a gas changes by of its original pressure at 0oC for each degree centigrade (or Celsius) rise in temperature at constant volume. If P_0 is the pressure of a given volume of a gas at 0oC and P_t is the pressure of the same volume of the gas (i.e., at constant volume) at t C, then

Constant Volume Gas Thermometer



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It consists of a glass bulb B connected to a tube A, through a capillary glass tube 'C'. The tube A is connected to a mercury reservoir R which is clamped on the board and can be lowered or raised whenever required to keep the volume of the air constant. The capillary tube C is provided with a three way stopper S and can be used to connect capillary and bulb as well as to disconnect tube from bulb B. A pointer is provided such that the end P is projecting inside from the upper part of A. A scale calibrated in 0°C is provided between A and R. The whole apparatus is leveled by adjusting the leveling screws. By adjusting the stopper, the bulb 'B' is filled with air or some gas and the pointer is adjusted so that tip of the pointer just touches the level of mercury in the tube A. After filling the bulb, it is kept in an ice bath for some time till the air inside the bulb attains the temperature of ice at which the mercury level becomes stationary. Now the reservoir R is adjusted so that the level of mercury in the tube A just touches the tip of the pointer P.

CONSTANT VOLUME GAS THERMOMETER

If P_o is the pressure of a given volume of a gas at 0°C and P_t is the pressure of the same volume of the gas (i.e., at constant volume) at $t^\circ\text{C}$, then

$$P_t = P_o + \frac{P_o}{273} \times t$$

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

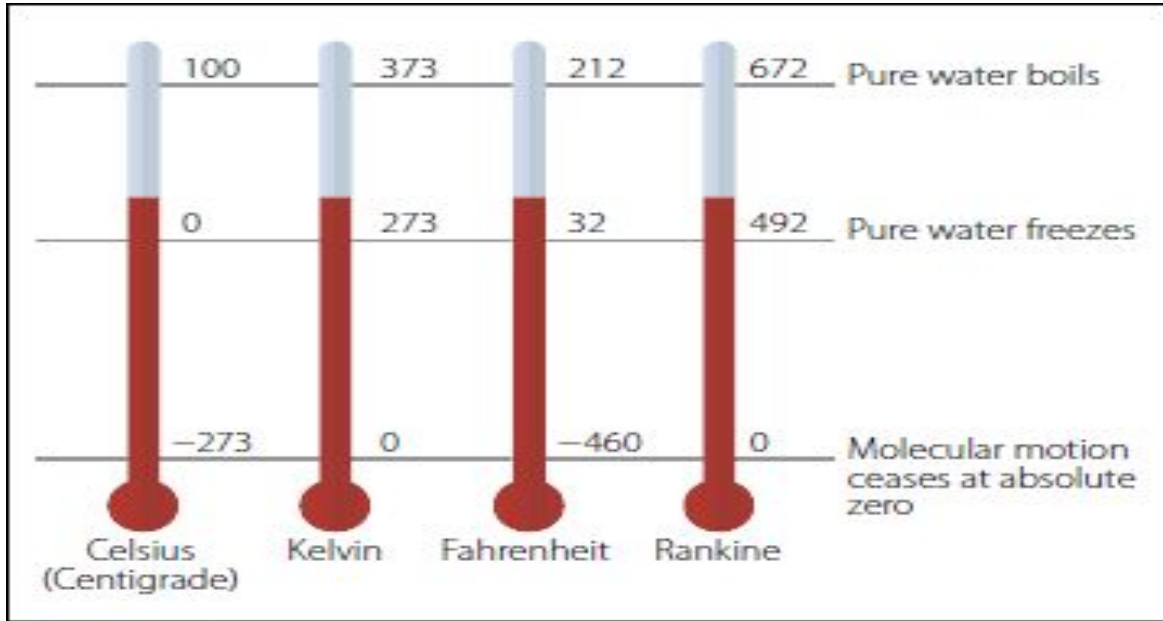
i.e., (or) $P_t = P_o + (1 + \gamma_v t)$ (1)

Where $\gamma_v = \frac{1}{273}$ is constant and is known as coefficient of increase of pressure

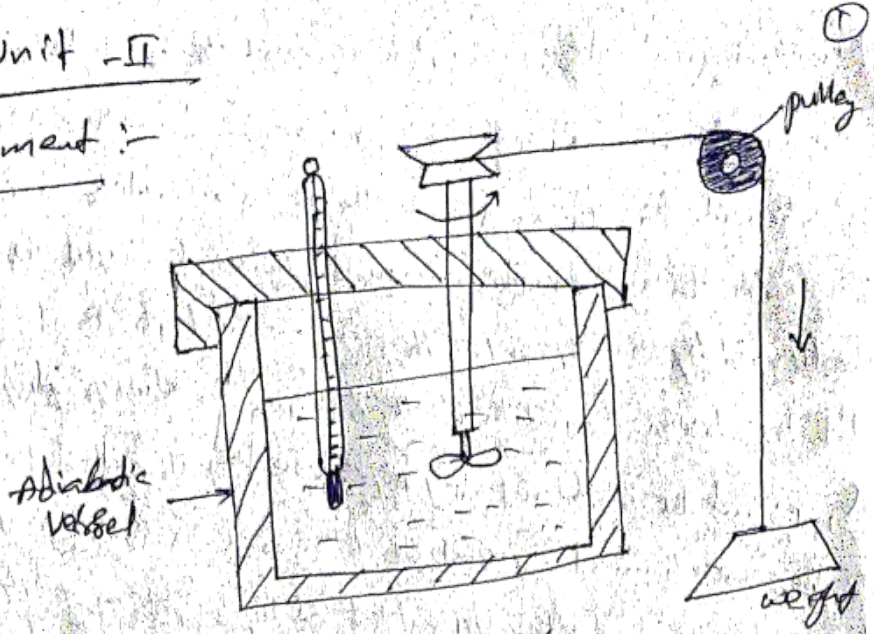
Scales of Temperature: There are three temperature scales in use Fahrenheit, Celsius and Kelvin. Fahrenheit temperature scale is a scale based on 32 for the freezing point of water and 212 for the boiling point of water, the interval between the two being divided into 180 parts.

The conversion formula for a temperature that is expressed on the Celsius (C) scale to its Fahrenheit (F) representation is: $F = 9/5C + 32$.

Celsius temperature scale also called centigrade temperature scale, is the scale based on 0 for the freezing point of water and 100 for the boiling point of water. Kelvin temperature scale is the base unit of thermodynamic temperature measurement in the International System (SI) of measurement. It is defined as $1/273.16$ of the triple point (equilibrium among the solid, liquid, and gaseous phases) of pure water.

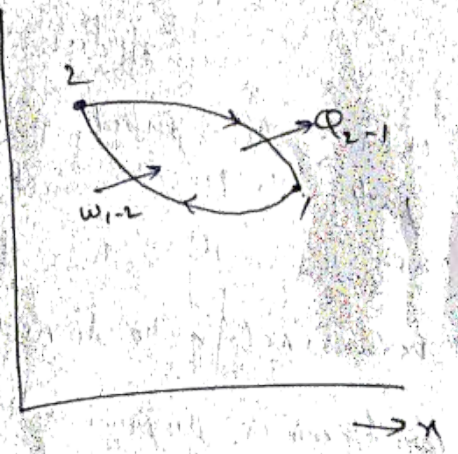


Joule's experiment :-



Let us consider a closed system which contains a known mass of water contained in an adiabatic vessel having a thermometer and a paddle wheel as shown in fig. Let a certain amount of work W_{1-2} be done upon the system by the paddle wheel. The quantity of work can be measured by the fall of weight which drives the paddle wheel through a pulley.

The system was initially at temperature t_1 , the same as that of atmosphere, and after work transfer let the temperature rise to t_2 . The pressure is always 1 atm. The process 1-2 undergone by the system



shown in fig (2) in generalized thermodynamic coordinates X, Y .

Fig. Cycle completed by a system with two energy interactions, adiabatic work transfer w_{1-2} followed by heat transfer q_{2-1} .

Let the insulation now be removed. The system and the surroundings interacted by heat transfer till the system returns to the original temperature t_1 , attaining the condition of thermal equilibrium

with the atmosphere. The amount of heat transfer Q_{2-1} from the system during this process, 2-1 shown in Fig 2, can be estimated. The system thus executes a cycle, which exhibits a definite amount of work input w_{1-2} to the system followed by the transfer of an amount of heat Q_{2-1} from the system. It has been found that this w_{1-2} is always proportional to the heat Q_{2-1} and the constant of proportionality is called the Joule's equivalent or the mechanical equivalent of heat. In this example, there are only two energy transfer quantities as the system performs a thermodynamic cycle. If the cycle involves many more heat and work quantities, the same result will be found. Expressed algebraically

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

$$\begin{matrix} w \propto Q \\ w = JQ \end{matrix}$$

where J is the Joule's equivalent.

The above equation is also expressed in the form

$$\oint dw = J \oint dQ$$

where the symbol \oint denotes the cyclic integral for the closed path which is the first law for a closed system undergoing a cycle.

In the S.I. system of units, both heat and work are measured in the derived unit of energy, the Joule. The

constant of proportionality, J , is therefore unity ($J = 1 \text{ Nm/J}$).

First law of thermodynamics:-

1). Work and energy are mutually convertible.

$$\oint dw = \int \delta q$$

for the same units of heat and work

$$\oint dw = \int \delta q$$

$$\boxed{\oint dw = \int \delta q}$$

2). Energy can neither be created nor destroyed but it can be transferred from one form to another. It is the law of Conservation of energy.

Its Q is the amount of heat

transferred to the system and

w is the amount of work transferred from the system during the process.

The net energy transfer ($Q - w$)

will be stored in the system. Energy in storage is neither heat nor work, and is given the name internal energy or simply, the energy of the system.

$$Q - w = \Delta E$$

where ΔE is the increase in the energy of the system.

$$Q = \Delta E + w$$

Here $Q, w, \Delta E$ are all expressed in the same units (in Joules)

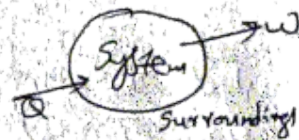
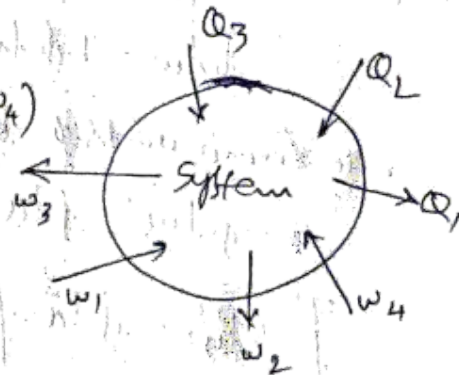


Fig: Heat and work interaction of a system with its surroundings in a process.

First law applied to a process: — It is there are more energy

transfer quantities involved in the process as shown in fig. the first law gives

$$Q_2 + Q_3 - Q_1 = \Delta E + (w_2 + w_3 - w_1 - w_4)$$



heat out from system is -ve (out)

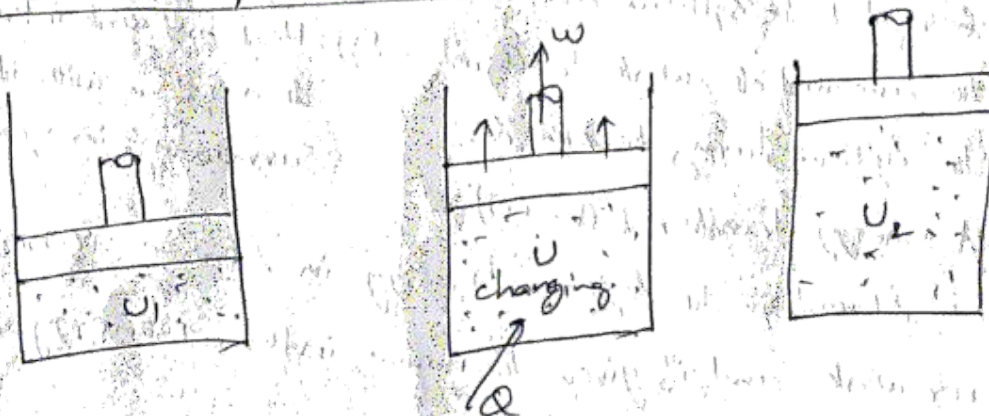
heat add to system is +ve (in)

work done on system is -ve (in)

work done by the system is +ve (out)

Fig: System-surroundings interaction in a process involving many energy fluxes

First law of Thermodynamics applied to closed system: — (non-flow process)



If the system follows a process which is not cyclic, the final state differs from the initial state, and the difference between energy input (heat transfer) and output (work transfer) results in a change in the energy content (internal energy) of the system.

Energy input - Energy output = change in internal energy

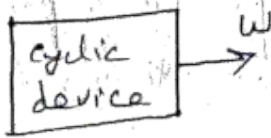
$$Q - w = U_2 - U_1$$

$$\Rightarrow Q = (U_2 - U_1) + w$$

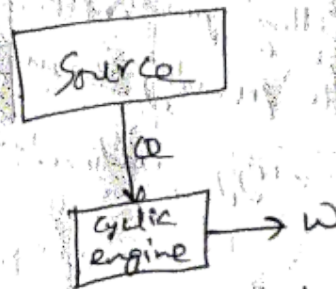
The above formula is called the non-flow energy Equations. This comprises the first Corollary or the first law of Thermodynamics. (5)

Corollaries of First law:-

- 1) For isolated systems, Q and w are zero, and therefore $(U_2 - U_1) = 0$. Thus the internal energy of an isolated system is constant.
- 2) The difference between heat supplied and work done during a non-flow process results in change in the property of the closed system, and is referred as internal energy.
- 3) A perpetual motion machine of first kind is impossible. A device that will deliver work continuously without input (i.e., without receiving energy) is called perpetual motion machine of the first kind (PMM I).



a). PMM - I



b). possible engine.

First law applied to a flow system :- In an open system,

the energy as well as matter cross the boundary. Any process undergone by an open system is called a flow process.

Flow processes may be sub-divided into two types,
1). Steady flow processes, and
2). Unsteady flow processes.

Steady flow processes! - Steady flow means that the rates of flow of mass and energy across the control surface are constant. i.e., the mass of fluid entering the system is equal to the mass of fluid leaving the system in a given time, and the transfer of energy must take place at a uniform rate.

Ex:- flow of steam through a nozzle and a steam boiler operating under a constant load. In order to maintain water level in boiler, the feed pump supplies water at exactly the same rate at which the steam is drawn off from the boiler.

Unsteady flow processes! - unsteady flow process is one in which the quantity of fluid (matter) in the system is not constant i.e., the mass of fluid entering the system is not the same as the mass of fluid (matter) leaving the system in a given time. Two simple cases of unsteady flow processes are tank filling process and tank emptying process. In both the cases the quantity of matter in the tank is not constant.

Steady flow energy equation!

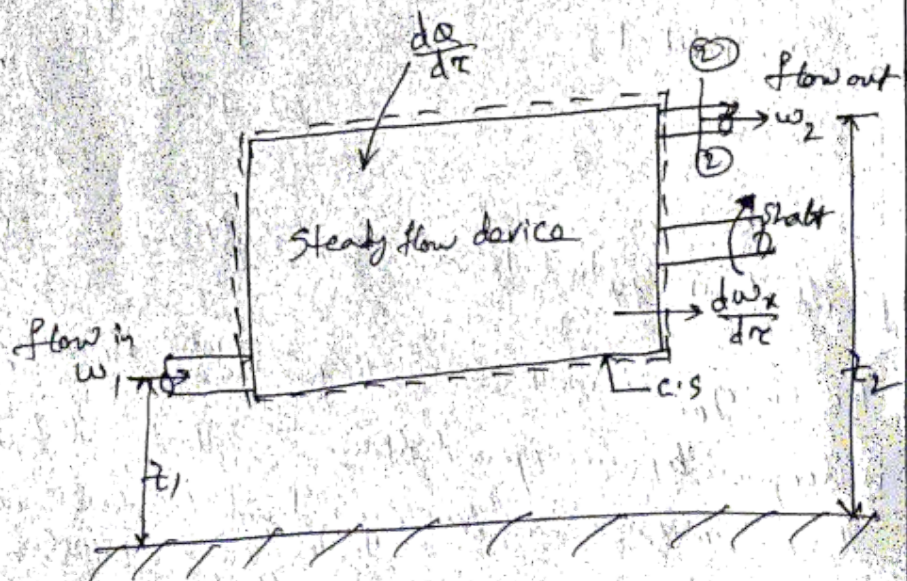


Fig. shows a Steady flow system, in which one stream (1) of fluid enters and another stream leaves the control volume. There is no accumulation of mass or energy within the control volume, and the properties at any location within the control volume are steady with time. Sections (1) and (2) indicate respectively the entrance and exit of the fluid across the control surface. The following quantities are

A_1, A_2 - cross-section of stream, m^2

w_1, w_2 - mass flow rate, kg/s

p_1, p_2 - 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

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

t - 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

$$w_1 = w_2$$

$$\frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2} \quad \text{--- (1)}$$

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.

External work is the shaft work (w_x).
The flow work is the displacement work done by the fluid of mass dm_1 at the inlet section 1 and that at the exit section, which are $(-P_1 \omega_1 dm_1)$ and $(+P_2 \omega_2 dm_2)$ respectively.

∴ Total work transfer

$$W = w_x - P_1 \omega_1 dm_1 + P_2 \omega_2 dm_2 \quad \text{--- (2)}$$

in the rate form

$$\begin{aligned} \frac{dW}{dt} &= \frac{dw_x}{dt} - P_1 \omega_1 \frac{dm_1}{dt} + P_2 \omega_2 \frac{dm_2}{dt} \\ &= \frac{dw_x}{dt} - P_1 \omega_1 w_1 + P_2 \omega_2 w_2 \quad \text{--- (3)} \end{aligned}$$

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 be equal to the total rate of flow of all energy streams leaving the control volume. This may be expressed in the following equation

$$w_1 e_1 + \frac{dQ}{dt} = w_2 e_2 + \frac{dw_x}{dt}$$

Substitute equation (3)

$$w_1 e_1 + \frac{dQ}{dt} = w_2 e_2 + \frac{dw_x}{dt} - w_1 P_1 \omega_1 + w_2 P_2 \omega_2$$

$$w_1 e_1 + \frac{dQ}{dt} + w_1 P_1 \omega_1 = w_2 e_2 + \frac{dw_x}{dt} + w_2 P_2 \omega_2 \quad \text{--- (4)}$$

where e_1, e_2 refers to the energy carried into or out of the control volume with unit mass of fluid. (9)

The specific energy e is given by

$$e = e_k + e_p + u$$

$$= \frac{v^2}{2} + zg + u$$

$$e_1 = \frac{v_1^2}{2} + z_1g + u_1$$

$$e_2 = \frac{v_2^2}{2} + z_2g + u_2$$

$e_k \rightarrow$ kinetic energy
 $e_p \rightarrow$ potential energy
 $u \rightarrow$ internal energy

Substitute e_1 and e_2 in equation (4)

$$\omega_1 \left(\frac{v_1^2}{2} + z_1g + u_1 \right) + \omega_1 p_1 \omega_1 + \frac{dQ}{dz}$$

$$= \omega_2 \left(\frac{v_2^2}{2} + z_2g + u_2 \right) + \omega_2 p_2 \omega_2 + \frac{dW_s}{dz}$$

$$\omega_1 \left[u_1 + p_1 \omega_1 + \frac{v_1^2}{2} + z_1g \right] + \frac{dQ}{dz}$$

$$h = u + p/\rho$$

$$h_1 = u_1 + p_1/\rho_1$$

$$h_2 = u_2 + p_2/\rho_2$$

$$= \omega_2 \left[u_2 + p_2 \omega_2 + \frac{v_2^2}{2} + z_2g \right] + \frac{dW_s}{dz}$$

$$\boxed{\omega_1 \left[h_1 + \frac{v_1^2}{2} + z_1g \right] + \frac{dQ}{dz} = \omega_2 \left[h_2 + \frac{v_2^2}{2} + z_2g \right] + \frac{dW_s}{dz}} \quad (5)$$

let $\omega_1 = \omega_2$

$$\omega = \omega_1 = \omega_2 = \frac{dm}{dz}$$

$$\boxed{h_1 + \frac{v_1^2}{2} + z_1g + \frac{dQ}{dm} = h_2 + \frac{v_2^2}{2} + z_2g + \frac{dW_s}{dm}} \quad (6)$$

$$\frac{dQ}{dz} \times \frac{dz}{dm} = \frac{dQ}{dm}$$

Equations (5) and (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) represents energy flow per unit mass of fluid (J/kg), whereas the terms in equation (5) represent energy flow per unit time (J/s).

Equation (6) can be written in the following form,

$$Q - w_x = (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1) \quad \text{--- (7)}$$

where Q and w_x refer to energy transfer per unit mass, in the differential form, the SFEE becomes

$$dq - dw_x = dh + v dv + g dz \quad \text{--- (8)}$$

when more than one stream of fluid enters and leaves the control volume (Fig below), the mass balance and energy balance for steady flow are given below.

mass balance

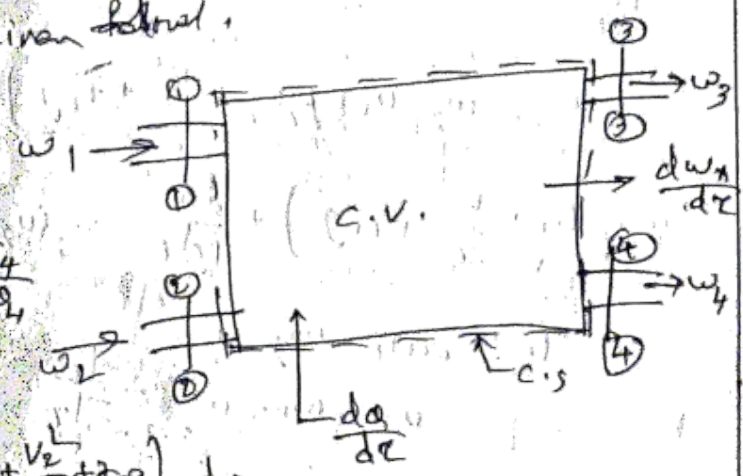
$$w_1 + w_2 = w_3 + w_4$$

$$\frac{A_1 V_1}{\rho_1} + \frac{A_2 V_2}{\rho_2} = \frac{A_3 V_3}{\rho_3} + \frac{A_4 V_4}{\rho_4}$$

Energy Balance

$$w_1 \left(h_1 + \frac{v_1^2}{2} + z_1 g \right) + w_2 \left(h_2 + \frac{v_2^2}{2} + z_2 g \right) + \frac{dq}{dt}$$

$$= w_3 \left(h_3 + \frac{v_3^2}{2} + z_3 g \right) + w_4 \left(h_4 + \frac{v_4^2}{2} + z_4 g \right) + \frac{dw_x}{dt}$$



Applications of SFEE :-

(11)

Nozzle :-

A nozzle is a device which increases the velocity of K.E.



of a fluid at the expense of its pressure drop. Fig. shows a nozzle which is insulated. The steady flow energy equation for the control surface gives

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

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

$$\frac{dw_s}{dm} = 0$$

$$z_1 = z_2$$

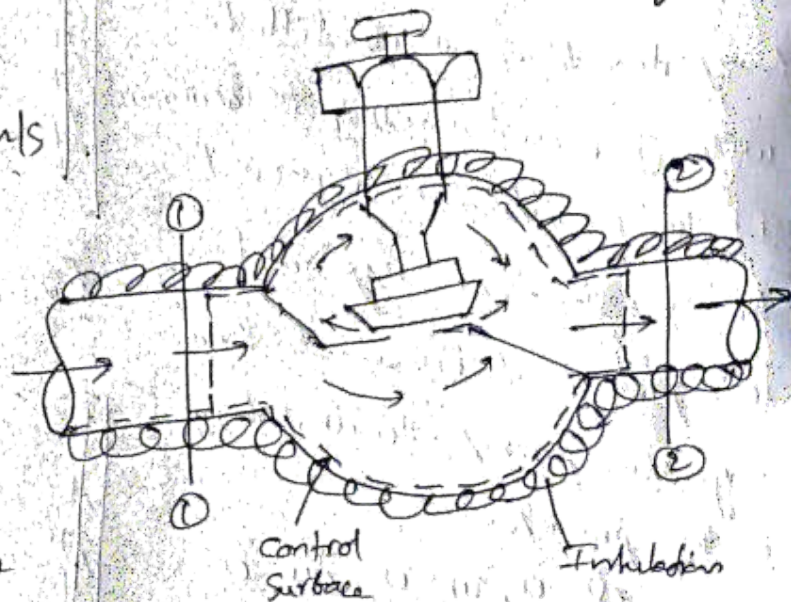
$$v_1 = \text{neglected}$$

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

$$\Rightarrow v_2 = \sqrt{2(h_1 - h_2)} \text{ m/s}$$

Throttling device :-

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



$$\frac{dq}{dm} = 0, \quad \frac{dw}{dm} = 0, \quad z_1 = z_2$$

(12)

$$\therefore h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2}$$

The pipe velocities in throttling are so low that the k.E. term are also negligible. So

$$h_1 = h_2$$

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

Free expansion process :-

A tank is divided into two compartments. one is filled with gas and another is vacuum. If the partition is removed the gas is free expanded. This process is known as free expansion process. No work done in this process.

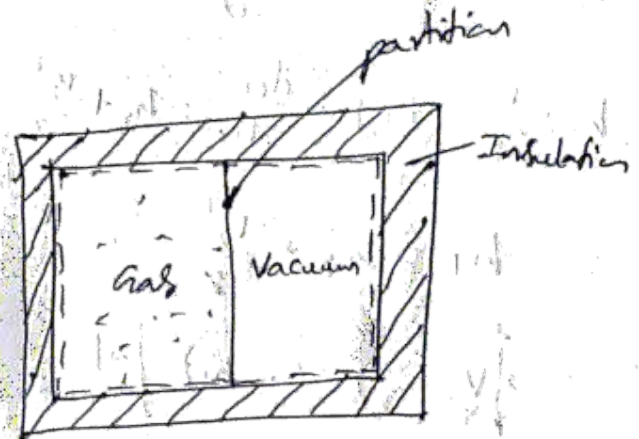


Fig. Before expansion

$$Q = 0, \quad W = 0, \quad du = 0$$

$$dv = 0, \quad T_1 = T_2$$

no change in temperature and hence $dh = 0, (H_2 = H_1)$

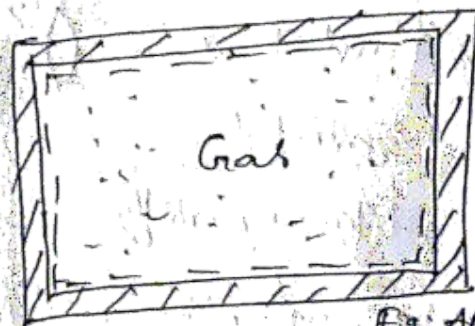
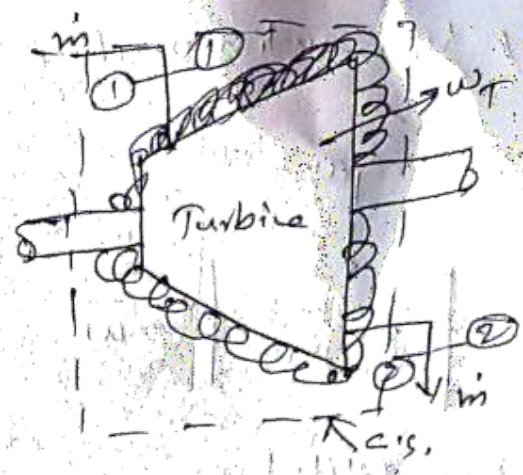


Fig. After expansion

Turbine :- For a turbine

which is well insulated,
 the flow velocities are often
 small, and the K.E. terms
 can be neglected. The SFEE becomes



$$\frac{dQ}{dm} = 0, z_1 = z_2, \text{K.E. neglected}$$

$$h_1 = h_2 + \frac{dw_t}{dm}$$

$$\frac{w_t}{m} = (h_1 - h_2)$$

It is seen that work is done by the fluid at the expense of its
 Enthalpy.

Compressor :- For an adiabatic pump or compressor, work is done
 upon the fluid and w is negative. So the SFEE becomes

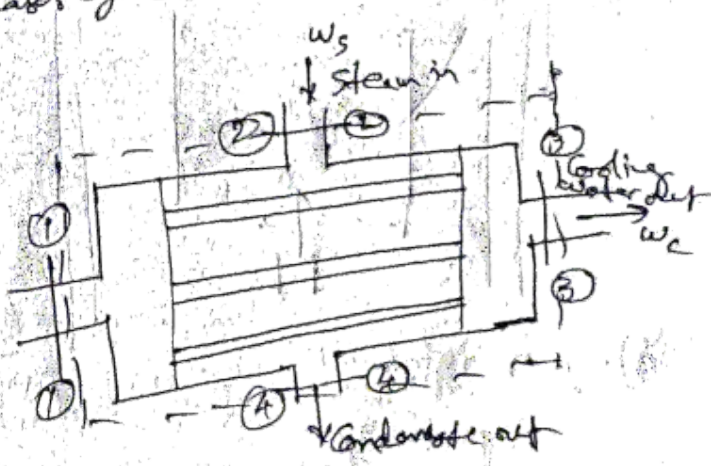
$$h_1 = h_2 - \frac{w_c}{m}$$

$$\frac{w_c}{m} = h_2 - h_1$$

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

Heat exchanger :-

K.E, P.E terms neglected,
 no external work done,
 no external heat
 interaction or heat loss



∴ SFEE becomes
 $w_s (h_2 - h_4) = w_c (h_3 - h_1)$

Fig: Steam Condenser

Perpetual motion machine of the first kind (PMM-I) :-



Fig. 1 PMM-I

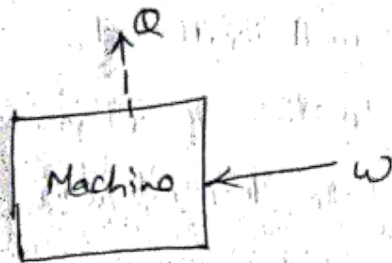


Fig. 2 The combination of PMM-I

no machine supply work without energy input. The first law states the principle of conservation of energy. Energy is neither created nor destroyed, but only gets transformed from one form to another.

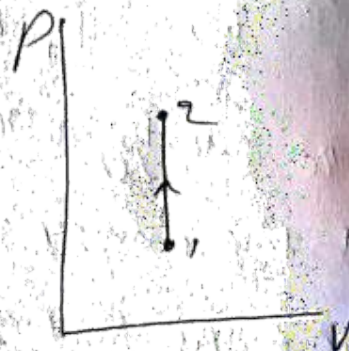
Fig. 1 shows, without input, engine develop work, it's not possible.

Fig. 2: machine take work but no production of heat, it's not possible.

These two are PMM-I.

First law applied to closed system :-

1). Reversible constant volume process (V constant) :-



a). P-V relationship

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

(for constant volume process)

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \text{ (general equation)}$$

⑥. Work done $\int p \cdot dv = \int p \cdot 0 = 0$

$w = 0$

First law of thermodynamics

$Q = \Delta E + w$

$\therefore Q = \Delta E = \Delta U$

⑦. change of internal energy

$u_2 - u_1 = m c_v (T_2 - T_1)$

⑧. Heat supplied $Q = \Delta U = m c_v (T_2 - T_1)$

⑨. change of enthalpy

$H_2 - H_1 = (u_2 - u_1) + (p_2 v_2 - p_1 v_1)$

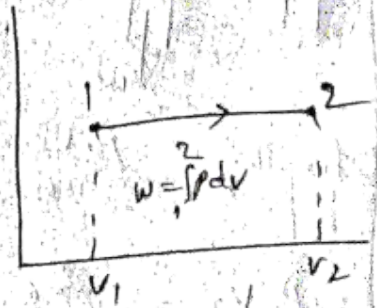
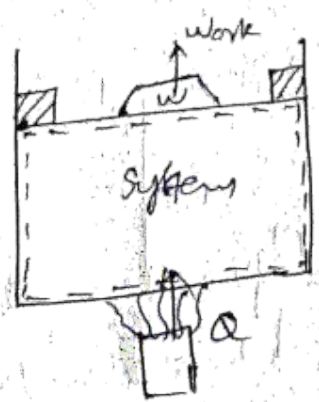
$= m c_v (T_2 - T_1) + m R (T_2 - T_1)$

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

$= m c_p (T_2 - T_1)$

$c_p - c_v = R$
 $c_p = R + c_v$

2). Reversible constant pressure process (p = constant) :-



a). p, v, T relationship $\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$ (general equation)

$\frac{v_1}{T_1} = \frac{v_2}{T_2}$ (for p = constant)

①. work done $W = p(V_2 - V_1)$
 $= mR(T_2 - T_1)$

①⑥
 $pV = RT$
 $p_1V_1 = RT_1$
 $p_2V_2 = RT_2$
 $p_2V_2 - p_1V_1$
 $= R(T_2 - T_1)$

②. change in internal energy

$Q = \Delta E + W$
 $\Delta u = u_2 - u_1 = mC_v(T_2 - T_1)$

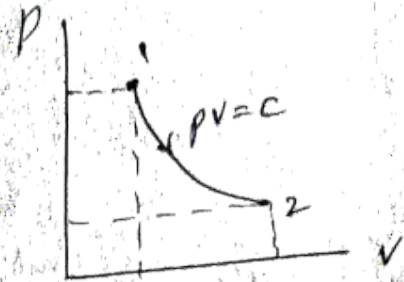
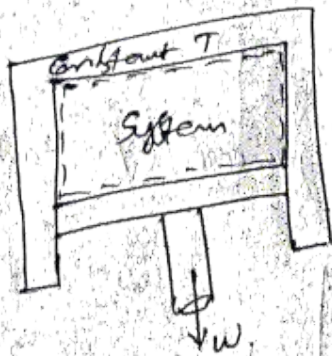
③. Heat Supplied or transferred

$Q = \Delta u + W$
 $= mC_p(T_2 - T_1)$

④. change in enthalpy

$dH = H_2 - H_1 = mC_p(T_2 - T_1)$

3). Reversible Constant Temperature process :-



a). p, v, T relationship $\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$

$p_1V_1 = p_2V_2$ (for $T = \text{Constant}$)

①. work done $W = p_1V_1 \ln \frac{V_2}{V_1}$

②. change internal energy

$\Delta u = u_2 - u_1 = 0$

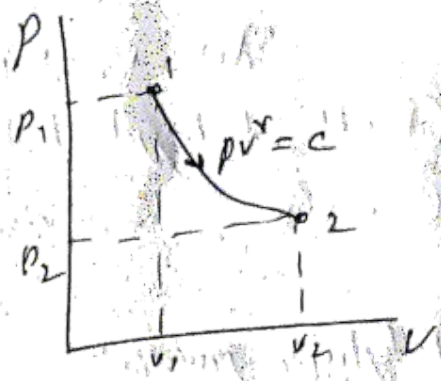
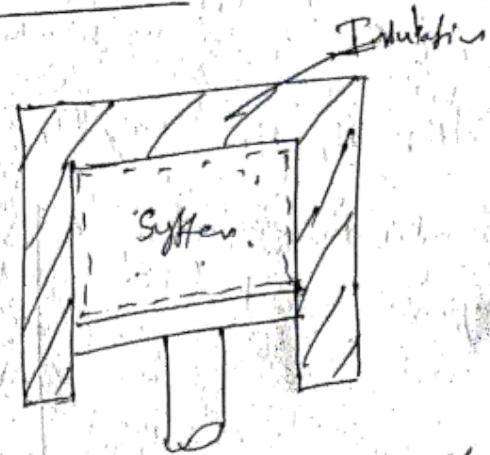
③. Heat supplied $Q_{1-2} = \Delta u + W = W = p_1V_1 \ln \frac{V_2}{V_1}$

②, change of enthalpy $dH = H_2 - H_1 = 0$

i.e., $H_2 = H_1$, because temperature is constant.

4) Adiabatic process -

It is a process in which neither receives nor gives heat to its surroundings



during its expansion or compression is called reversible adiabatic process.

②. P, V, T relationship

$$PV^\gamma = c$$

$$P_1 V_1^\gamma = P_2 V_2^\gamma$$

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

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

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

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

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

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

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

$$\frac{T_1}{T_2} = \frac{V_1}{V_2} \times \frac{P_1}{P_2} = \left(\frac{P_1}{P_2}\right)^{-1/\gamma} \times \frac{P_1}{P_2}$$

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

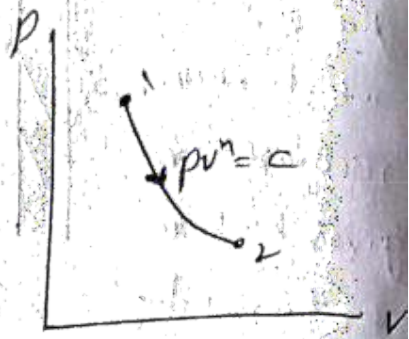
(b) work done $w = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$

(c) change in internal energy
 $du = u_2 - u_1 = m c_v (T_2 - T_1)$

(d) Heat supplied $Q_{1-2} = 0$

(e) change in enthalpy, $dH = H_2 - H_1 = m c_p (T_2 - T_1)$

Polytropic process! — It is also known as the general law for the expansion and compression of gases.



$P V^n = \text{constant}$

(a) P, V, T relationship

$P_1 V_1^n = P_2 V_2^n$

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

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

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

(b) work done $w_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n - 1}$

(c) Heat supplied or transferred

$Q_{1-2} = w_{1-2} + du$

$= \frac{P_1 V_1 - P_2 V_2}{n - 1} + m c_v (T_2 - T_1)$

$= \frac{m R (T_2 - T_1)}{n - 1} + \frac{m R}{\gamma - 1} (T_2 - T_1) \quad \left(\because c_v = \frac{R}{\gamma - 1}\right)$

$$= mR (T_1 - T_2) \left[\frac{1}{n-1} - \frac{1}{\gamma-1} \right] \quad (19)$$

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

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

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

(d) change in internal energy

$$dU = U_2 - U_1 = mC_v (T_2 - T_1)$$

(e) change in enthalpy

$$dH = H_2 - H_1 = mC_p (T_2 - T_1)$$

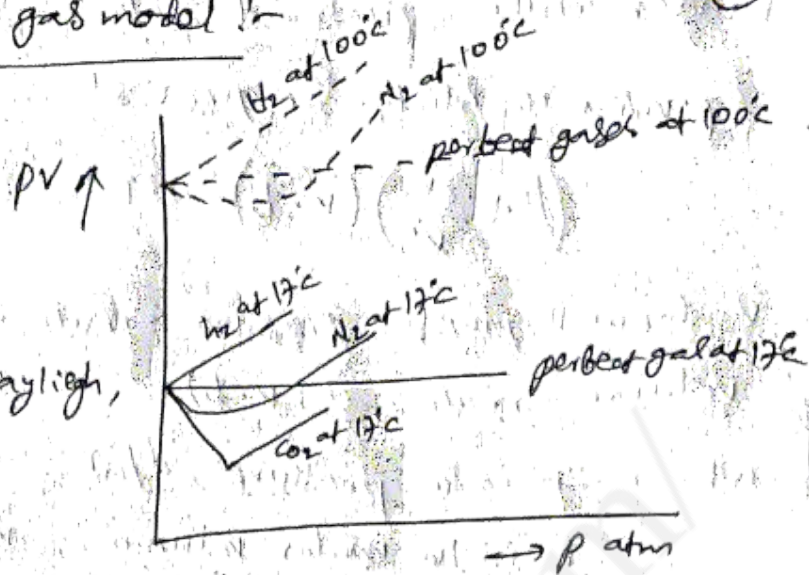
Summary of processes for perfect gas (unit mass) :-

process	Index	Heat supplied	work done	P, V, T relationship	change in internal energy	change in enthalpy	Specific heat
Constant pressure process	$n = 0$	$c_p (T_2 - T_1)$	$P (V_2 - V_1)$	$\frac{T_2}{T_1} = \frac{V_2}{V_1}$	$m c_v (T_2 - T_1)$	$m c_p (T_2 - T_1)$	c_p
Constant Volume process	$n = \infty$	$c_v (T_2 - T_1)$	0	$\frac{T_1}{T_2} = \frac{P_1}{P_2}$	$m c_v (T_2 - T_1)$	$m c_p (T_2 - T_1)$	c_v
Constant temperature process	$n = 1$	$P_1 V_1 \ln \left(\frac{V_2}{V_1} \right)$	$P_1 V_1 \ln \left(\frac{V_2}{V_1} \right)$	$P_1 V_1 = P_2 V_2$	$m c_v (T_2 - T_1)$	$m c_p (T_2 - T_1)$	∞
Adiabatic process	$n = \gamma$	0	$\frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{\gamma}{\gamma - 1} (T_2 - T_1)$	$P_1 V_1^\gamma = P_2 V_2^\gamma$	$m c_v (T_2 - T_1)$	$m c_p (T_2 - T_1)$	0
Polytropic process	$n = n$	$\frac{(c_p - n) m c_p (T_2 - T_1)}{(n - 1)(c_p - 1)}$	$\frac{P_1 V_1 - P_2 V_2}{n - 1}$ or $\frac{P_1}{n - 1} (T_2 - T_1)$	$P_1 V_1^n = P_2 V_2^n$	$m c_v (T_2 - T_1)$	$m c_p (T_2 - T_1)$	$c_n = c_v \left(\frac{\gamma - n}{1 - n} \right)$

Deviations from perfect gas model

(21)

Figure shows the deviations of real gases from perfect gases by the experimental results Lord Rayleigh, those curves are called isotherms.



According to Boyle's law

$PV = \text{constant}$ at all pressures and variation of pressure with PV is a straight line, but this is only for perfect gas and real gases are not showing straight lines.

At low pressures for H_2 PV increases as P increases

for N_2 PV decreases as P increases.

For perfect gas PV remain constant as P increase, for CO_2 , and N_2 , PV first decreases and then increase as P increases, for perfect gas PV remains constant as P increases.

all real gases have higher values of PV than that of a perfect gas.

Vander waal's Equation of State? Vanderwaal proposed a

Equation of States for gases as

$$\left(p + \frac{a}{v^2}\right)(v-b) = RT$$

Vander waal proposed pressure correction as $\left(p + \frac{a}{v^2}\right)$ and volume correction as $(v-b)$.

where p is the pressure, N/m^2

v is the molar volume, $m^3/kg\text{ mole}$

T is the temperature, K

R is the gas constant = 8.314 kJ/kg mole

a is the constant, $N \cdot m^4/(kg \text{ mole})^2$

b is the constant, $m^3/kg \text{ mole}$

Compressibility chart:-

The Compressibility factor (z) of any gas is a function of only two properties, usually temperature and pressure, so that

$$z = \frac{pv}{RT}$$

$z = f(T_r, P_r)$ except near

the critical point. The

value of z for any real gas may be less or

more than unity, depending

on pressure and temperature conditions of the gas.

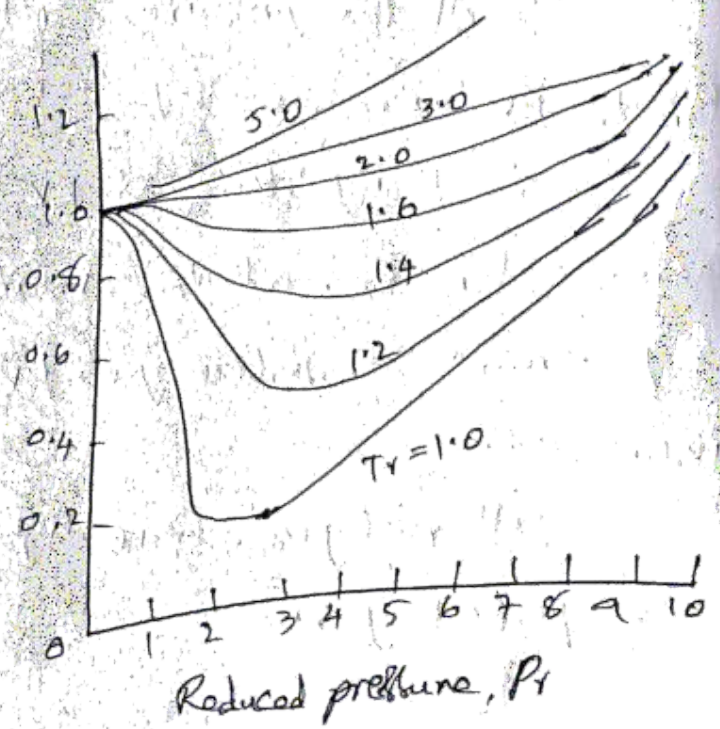
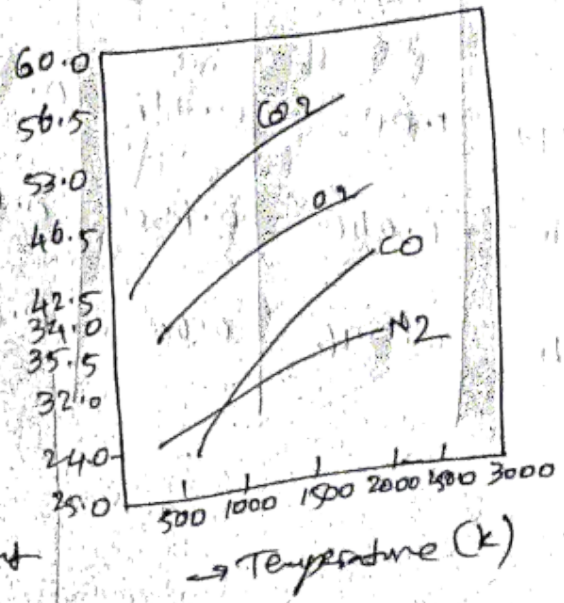


Fig: Generalized Compressibility chart

The general compressibility chart is plotted with Z versus P_r for various values of T_r . This is constructed by plotting the known data of one or more gases and can be used for any gas. Such chart is shown in fig. This chart gives best results for the regions well removed from the critical state for all gases.

Variation of specific heat with temperature:

Specific heat of any gas increases with increasing temperature because increase of vibration of molecules at high temperature. The vibrations are caused because of collisions among molecules which are significant at high temperatures.



The temperature range of 300 K to 1500 K the specific heat is a linear function of temperature and may be expressed as $c_p = a + kT$, $c_v = b + kT$ where a, b, k are constants.

characteristic gas constant $R = c_p - c_v$
 $= (a + kT) - (b + kT)$
 $= a - b$

above 1500 k

(24)

$$c_p = a + k_1 T$$

$$c_v = b + k_1 T + k_2 T^2$$

Gas Tables: - By using gas tables, we read the properties of gases.

Gas	molecular weight	c_p (kJ/kgk)	c_v (kJ/kgk)	$R = c_p - c_v$	$\gamma = \frac{c_p}{c_v}$	$z_c = \frac{P_c V_c}{R_o T_c}$
Air	28.97	1.005	0.718	0.287	1.4	0.204
CO ₂	44	0.840	0.650	0.190	1.3	0.274
SO ₂	64	0.796	0.67	0.126	1.19	0.268

1). A stationary mass of gas is compressed without friction⁽²⁵⁾ from an initial state of 0.3 m^3 and 0.105 MPa to a final state of 0.15 m^3 and 0.105 MPa , the pressure remaining constant during the process. There is a transfer of 37.6 kJ of heat from the gas during the process. How much does the internal energy of the gas change?

Soln: First law for a stationary system in a process gives

$$Q = \Delta U + W$$

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

$$\text{Here } W_{1-2} = \int_{V_1}^{V_2} p \, dV = p(V_2 - V_1)$$

$$= 0.105(0.15 - 0.30) \text{ MJ}$$

$$= -15.75 \text{ kJ}$$

$$Q_{1-2} = -37.6 \text{ kJ}$$

∴ from equation (1)

$$-37.6 = U_2 - U_1 + (-15.75)$$

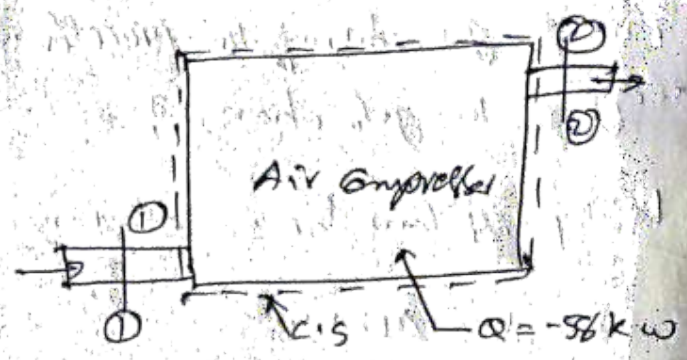
$$= (U_2 - U_1) - 15.75$$

$$\therefore (U_2 - U_1) = -21.85 \text{ kJ}$$

The internal energy of the gas decreases by 21.85 kJ in the process.

2). Air flows steadily at the rate of 0.5 kg/s through an air compressor, entering at 7 m/s velocity, 100 kPa pressure, and $0.95 \text{ m}^3/\text{kg}$ volume, and leaving at 5 m/s , 700 kPa and $0.19 \text{ m}^3/\text{kg}$. The internal energy of the air leaving is 90 kJ/kg .

greater than that of the air entering. Cooling water in the compressor jackets absorbs heat from the air at the rate of 58 kW. (a). Compute the rate of shaft work input to the air in kW. (b). Find the ratio of the inlet pipe diameter to outlet pipe diameter.



Soln $v_1 = 7 \text{ m/s}$
 $P_1 = 100 \text{ kPa}$
 $\rho_1 = 0.95 \text{ m}^3/\text{kg}$

$v_2 = 5 \text{ m/s}$
 $P_2 = 700 \text{ kPa}$
 $\rho_2 = 0.19 \text{ m}^3/\text{kg}$
 $u_2 = (u_1 + 90) \text{ kJ/kg}$

(a). writing the steady flow energy equation

$$w \left(u_1 + P_1 v_1 + \frac{v_1^2}{2} + z_1 g \right) + \frac{dq}{dt} = w \left(u_2 + P_2 v_2 + \frac{v_2^2}{2} + z_2 g \right) + \frac{dw_x}{dt}$$

$$= \frac{dw_x}{dt} = -w \left[(u_2 - u_1) + (P_2 v_2 - P_1 v_1) + \frac{v_2^2 - v_1^2}{2} + (z_2 - z_1)g \right] + \frac{dq}{dt}$$

$$= -0.5 \left[90 + (7 \times 0.19 - 1 \times 0.95) 100 + \frac{(5^2 - 7^2) \times 10^{-3}}{2} + 0 \right] - 58$$

$$= -0.5 [90 - 38 - 0.012] - 58$$

$$= -122 \text{ kW}$$

Rate of work input is 122 kW

(b). From mass balance, we have

$$w = \frac{A_1 v_1}{\rho_1} = \frac{A_2 v_2}{\rho_2}$$

$$\frac{A_1}{A_2} = \frac{\rho_2}{\rho_1} \cdot \frac{v_2}{v_1} = \frac{0.19}{0.95} \cdot \frac{5}{7} = 3.57$$

$$\therefore \frac{d_1}{d_2} = \sqrt{3.57} = 1.89$$

PROPERTIES OF PURE SUBSTANCE: UNIT-IV ①

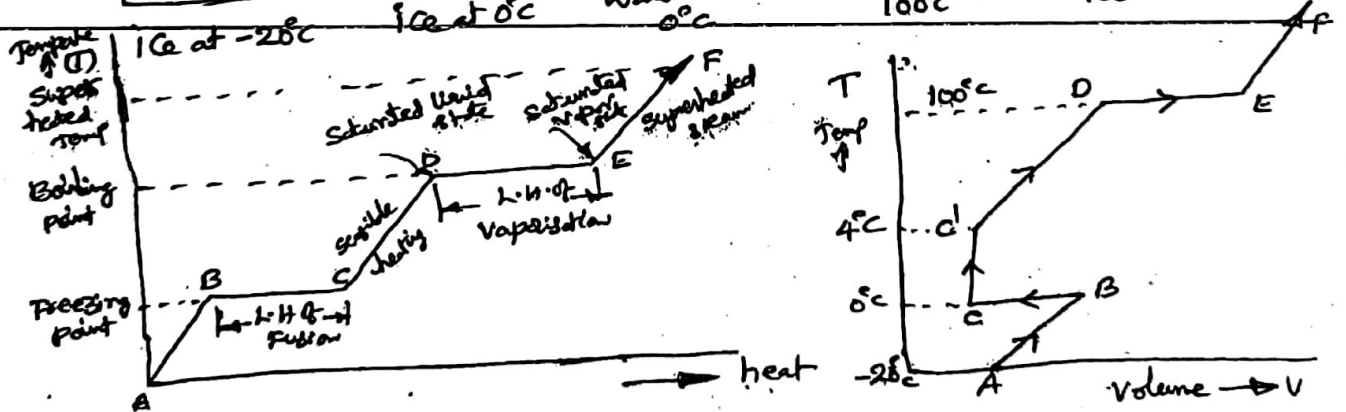
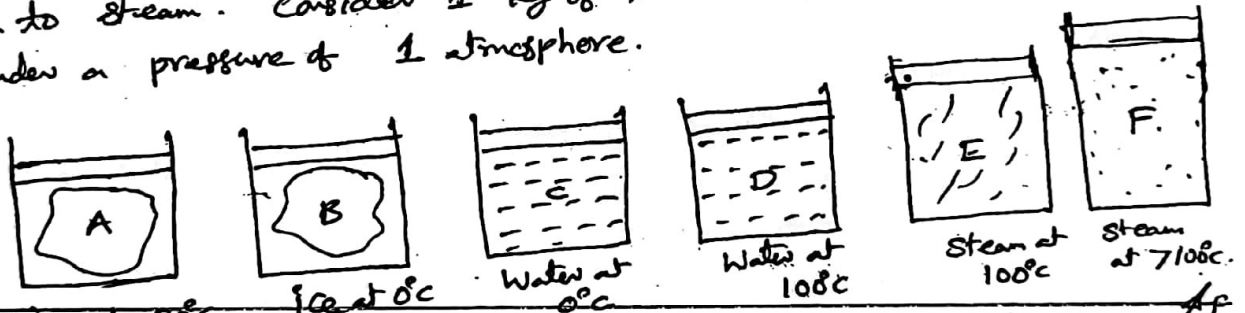
A pure substance may be defined as a substance, which is chemically homogeneous and has a fixed chemical composition. Any substance that appears with invariable chemical composition in either phase (or) a combination of phases may be treated as a pure substance. Water, nitrogen, helium and CO_2 are pure substances.

Phases of a pure substance:- There are three principle phases of a substance. Solid, liquid and gaseous phases.

We will study the behaviour of water in all the three phases in thermodynamic plots on P-V, P-T, T-S and h-s co-ordinates.

* Important.
Phase Transformation Σ Ice at $-20^\circ C$ to superheated steam above $100^\circ C$

To understand the properties of a substance during its phase change let us consider the example of ice converting into steam. Consider 1 kg of ice at $-20^\circ C$ in a cylinder under a pressure of 1 atmosphere.



Latent heat of Fusion (Enthalpy of fusion):- The quantity of heat required to convert solid into liquid at a constant temperature is known as Latent heat of fusion (or) Enthalpy of fusion. For water, latent heat of fusion at 1 atmosphere is 335 kJ/kg .

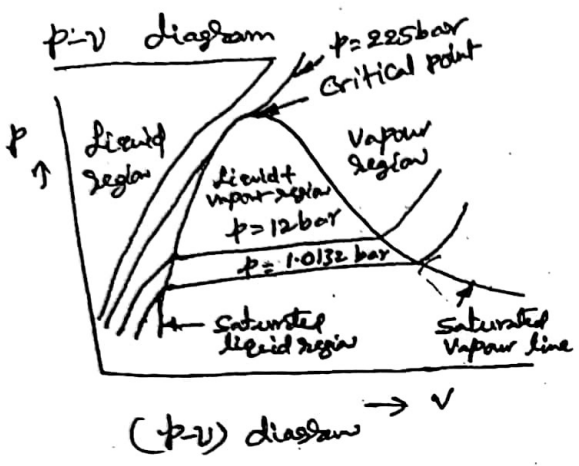
Freezing point Temperature:- The temp at which the substance changes its phase is known as freezing point temperature.

The freezing point temp. depends on the pressure. It increases with increase of pressure.

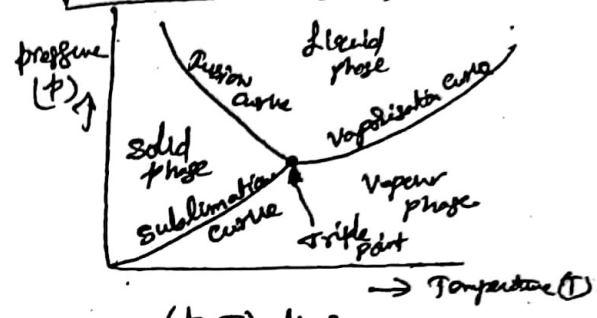
Latent heat of vaporization:-

The quantity of heat required to convert liquid into steam at constant temperature is known as latent heat of vaporisation. at 1 atm sphere is 2256.9 KJ/kg.

The quantity of heat required to convert liquid into steam at constant temperature is known as latent heat of vaporisation. For water latent heat of vaporisation at 1 atm sphere is 2256.9 KJ/kg.



Pressure-Temperature diagram of a pure substance (p-T) diagram.



(p-T) diagram
The p-T diagram of a pure substance is generally called phase diagram. Since, it shows solid, liquid and vapour regions of a substance simultaneously.

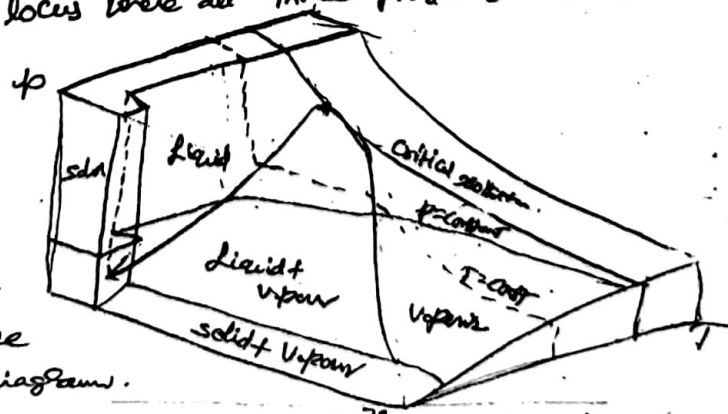
Each single phase of a pure substance is separated by saturation lines. The sublimation line separates the solid and vapour regions. The vaporization line separates the liquid and vapour regions, and the fusion line separates the solid and liquid regions.

The slope of the fusion line is negative. It indicates that the melting point of it decreases with increasing pressure.

Triple point:- The sublimation, fusion and vaporization lines meet a point called triple point. Triple point can be defined as a locus where all three phases of a substance co-exist.

p-v-T diagrams

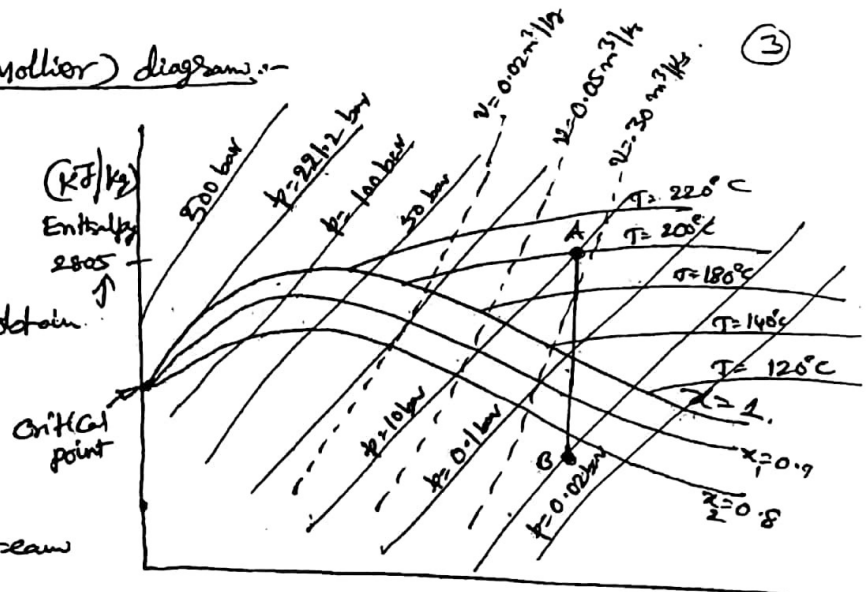
The relationship among pressure, specific volume and temp. of a pure substance can be better understood by the three dimensional p-v-T diagram.



The figure shows a p-v-T surface for water, which expands on freezing. It shows p-v, p-T and T-v diagrams simultaneously on three dimensional plot. A constant temp. line is drawn in the figure passing through the critical point is called critical isotherm.

Enthalpy - Entropy (Mollier) diagram:-

The enthalpy-entropy diagram is referred as Mollier diagrams. It is most commonly used to obtain properties of steam with reasonable accuracy, while analysing the steady flow devices such as steam turbines, nozzles etc.



The use of the mollier chart eliminates the complex calculation of work and it is also convenient to use.

In (h-s) chart, pressure range is from 0.01 bar to 1000 bar and a temperature up to 800°C. The saturation curve (above $x=1$), below saturation line, the dryness fraction is below 1, and called wet region. The properties above $x=1$ called dry & superheated region.

Important Terms for Steam

- Wet steam:- steam contains moisture (or) particles of water in suspension is called wet steam. Evaporation of water is not complete.
- Dry steam:- when wet steam is further heated, it does not contain any suspended particles of water is known as dry saturated steam. It behaves as a perfect gas. steam absorbed full latent heat.
- superheated steam:- when dry steam is further heated at constant pressure, thus raising its temperature, it is said to be superheated steam. Since pressure is constant, the volume of superheated steam increases. superheated steam is obtained in a super heater.
- Dryness fraction (or) Quality of steam:- it is the ratio of the mass of the actual dry steam to the mass of dry steam + the mass of wet steam.

$$\therefore x = \frac{m_d}{(m_d + m_w)} = \frac{m_d}{m}$$
 where $m_d \rightarrow$ Mass of dry steam
 $m_w \rightarrow$ Mass of wet steam.
- Sensible heat of water:- it is the amount of heat absorbed by 1 kg of water, when heated at constant pressure without phase change.

$$\therefore \text{sensible heat} = \text{mass of water} \times \text{specific heat} \times \text{rise in temperature}$$

$$\therefore h_f = m_w \times 4.187 (dT)$$

6. Latent heat of vaporization:- It is the amount of heat absorbed to evaporate 1 kg of water at its boiling temperature (or) saturation temperature without change of temperature. It is denoted by h_{fg} .
 If it is wet steam, then latent heat of vaporization = $x \cdot h_{fg}$.

7. Enthalpy (or) Total heat of steam: It is the amount of heat absorbed by water to its saturation temperature plus heat absorbed during evaporation.

Enthalpy (or) Total heat of steam = sensible heat + latent heat

$$h = h_f + h_{fg} = h_g \rightarrow \text{Dry steam}$$

$$h = h_f + x \cdot h_{fg} \rightarrow \text{Wet steam}$$

* $[T_{sup} - T_{sat}] \rightarrow$ degree of superheat

$$h = h_g + C_p [T_{sup} - T_{sat}] \rightarrow \text{Superheated steam}$$

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 by m^3/kg .

$$\text{Volume of wet steam} = x \cdot v_g + (1-x) v_f$$

$v_f \rightarrow$ volume of water per kg
 $v_g \rightarrow$ volume of dry steam per kg.

Since v_f is very small,

$$\therefore \text{Volume of 1 kg of wet steam} = v = x v_g, m^3/kg.$$

For Dry steam:- $v_g \text{ } m^3/kg$.

For Super heated steam, $\frac{v_{sup}}{v_{sat}} = \frac{v_g}{v_{g, sat}}$

Steam Tables and their use:-

The properties of dry saturation steam like its temperature of formation [saturation temp], sensible heat, latent heat, enthalpy, total heat, specific volume, entropy vary with pressure can be found explicitly.

Internal energy of steam (u) It is the actual heat energy stored in steam, above the freezing point of water.

Internal energy of steam = Enthalpy (or) Total heat - External work done during evaporation.

For Wet steam, internal energy, $u = h_f + x \cdot h_{fg} - 100 p \cdot x \cdot v_g \text{ } KJ/kg$

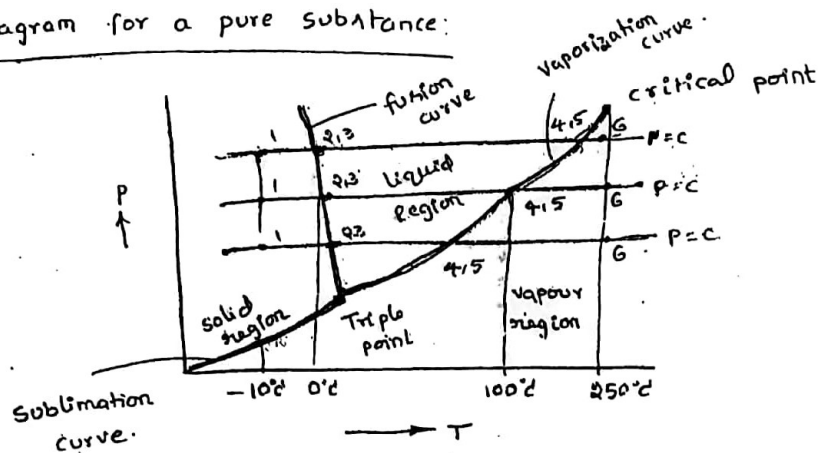
For Dry steam, $u = h_g + h_{fg} - 100 p v_g, \text{ } KJ/kg$

For Superheated steam, $u = h_g + C_p (t_{sup} - t_{sat}) - 100 p v_{sup}$.

Measurement of Dryness fraction of Steam

1. Barrel Calorimeter
2. Separating Calorimeter
3. Throttling Calorimeter
4. Combined Separating and throttling calorimeter.

P-T Diagram for a pure substance:



phase Equilibrium Diagram on P-T coordinates

The state changes of a pure substance upon slow heating at different constant pressures are shown in fig. If these state changes are plotted on P-T coordinates the diagram as shown in fig. If the heating of ice at -10°C to steam at 250°C at the constant pressure of 1 atm is considered 1-2 is the solid (ice) heating

2-3 is the melting of ice at 0°C , 3-4 is the liquid heating 4-5 is the vaporization of water at 100°C and 5-6 is the heating in the vapour phase. The process will be reversed from state 6 to state 1 upon cooling. The curve passing through the 2,3 points is called the fusion curve and the curve passing through 4,5 points

[which indicate the vaporization or condensation at diff. temp. & pressures] is called the vaporization curve. If the vapor pressure of a solid is measured at diff. temperatures, and these are plotted the sublimation curve will be obtained. The fusion curve, the vaporization curve and the sublimation curve meet at the triple point.

The slopes of the sublimation and vaporization curves for all substances are positive. The slope of the fusion for most substances is positive ^{but} for water it is negative.

⑤
PROB Calculate the enthalpy of 1 kg of steam at a pressure of 8 bar and dryness fraction of 0.8. How much heat would be required to raise 2 kg of this steam from water at 20°C?

SOL. Enthalpy of 1 kg of steam.

From steam tables, corresponding to a pressure of 8 bar, we find that

$$h_f = 720.9 \text{ kJ/kg} \text{ and } h_{fg} = 2046.5 \text{ kJ/kg.}$$

We know that enthalpy of 1 kg of wet steam,

$$h = h_f + x \cdot h_{fg} = 720.9 + 0.8 \times 2046.5 = 2358.1 \text{ kJ.}$$

Heat required to raise 2 kgs of this steam from water at 20°C.

$$\text{heat already in water} = 4.2 \times 20 = 84 \text{ kJ.}$$

and heat required per kg of steam,

$$= 2358.1 - 84 = 2274.1 \text{ kJ.}$$

$$\text{heat required for 2 kgs of steam} = 2 \times 2274.1 = 4548.2 \text{ kJ.}$$

PROB Determine the quantity of heat required to produce 1 kg of steam at a pressure of 6 bar at a temperature of 25°C, under the following conditions.

- 1) When the steam is wet having a dryness fraction of 0.9
- 2) When the steam is dry saturated
- 3) When the steam is superheated at a constant pressure at 25°C assuming the mean specific heat of superheated steam to be 2.3 kJ/kg.K.

SOL. Given, pressure, $p = 6 \text{ bar}$, $t_w = 25^\circ\text{C}$; $x = 0.9$; $t_{sp} = 250^\circ\text{C}$
 $C_p = 2.3 \text{ kJ/kg.K.}$

From steam tables corresponding to a pressure of 6 bar, we find that
 $h_f = 670.4 \text{ kJ/kg}$; $h_{fg} = 2085 \text{ kJ/kg}$ and $t_{sat} = 158.8^\circ\text{C}.$

1) When the steam is wet,

enthalpy (or) total heat of 1 kg of steam,

$$h = h_f + x \cdot h_{fg} = 670.4 + 0.9 \times 2085 = 2546.9 \text{ kJ.}$$

Since the water is at a temperature of 25°C,

$$\text{Heat already in water} = 4.2 \times 25 = 105 \text{ kJ.}$$

$$\text{Heat actually required} = 2546.9 - 105 = \underline{2441.9 \text{ kJ.}}$$

2) When the steam is dry saturated

$$h_g = h_f + h_{fg} = 670.4 + 2085 = h_g = 2755 \text{ kJ/kg}$$

$$\text{Heat actually required} = h_g - 105 = 2755 - 105 = 2650.4 \text{ kJ.}$$

3. When the steam is superheated

$$h_{sup} = h_g + C_p [t_{sup} - t_{sat}] = 2755.4 + 2.3(250 - 158.8) = 2965.16 \text{ kJ/kg}$$

Heat actually treated = $2965.16 - 105 = 2860.16 \text{ kJ}$

PROB determine the condition of steam in the following cases.

1. At a pressure of 10 bar and temperature 200°C
2. At a pressure of 10 bar and volume $0.175 \text{ m}^3/\text{kg}$.

1. At a pressure of 10 bar and temperature 200°C

From steam tables, corresponding to a pressure of 10 bar, we find that

$$v_g = 0.194 \text{ m}^3/\text{kg}; h_f = 762.6 \text{ kJ/kg}; \text{ and } t_{sat}$$

$$t_{sat} = 179.9^\circ\text{C}$$

Since the saturation temperature at 10 bar is 179.9°C is lower than the given temperature of steam 200°C , the given steam is superheated.

$$\text{The degree of superheat} = T_{sup} - T_{sat} = 200 - 179.9 = 20.1^\circ\text{C}$$

2. Condition of steam at a volume of $0.175 \text{ m}^3/\text{kg}$

Since the volume of given steam ($0.175 \text{ m}^3/\text{kg}$) is less than specific volume of dry saturated steam ($0.194 \text{ m}^3/\text{kg}$), therefore, the given steam is wet. The dryness fraction = $\frac{v_{\text{wet steam}}}{v_{\text{dry steam}}} = \frac{0.175}{0.194} = 0.902$

PROB Steam enters an engine at a pressure of 12 bar with a 67°C of superheat. It is exhausted at a pressure of 0.15 bar and 0.95 dry. Find the drop in enthalpy of the steam.

SOL From steam tables, corresponding to 12 bar, $h_g = h_f + h_{fg} = 2782 \text{ kJ/kg}$

Enthalpy (a) total heat of 1 kg of steam (superheated) is

$$h_{sup} = h_g + C_p [T_{sup} - T_{sat}] = 2782 + 2 \times 67$$

$$= 2916.7 \text{ kJ/kg}$$

[∵ since $C_p = 2 \text{ kJ/kg K}$ then $T_{sup} - T_{sat} = 67^\circ\text{C}$ given]

From steam tables, at pressure of 0.15 bar,

$$h_f = 226 \text{ kJ/kg}; h_{fg} = 2373.2 \text{ kJ/kg}$$

Enthalpy (b) total heat of 1 kg of wet steam

$$= h_{wet} = h_f + x h_{fg} = 226 + 0.95 \times 2373.2 = 2411 \text{ kJ/kg}$$

$$\text{Drop in enthalpy of steam} = h_{sup} - h_{wet} = 2916.7 - 2411 = 505.7 \text{ kJ/kg}$$

PROB Determine the volume of 1 kg of superheated steam at a pressure of 20 bar and a temp of 300°C .

SOL Given, $p = 20 \text{ bar}; T_{sup} = 300^\circ\text{C} = 300 + 273 = 573 \text{ K}$

From steam tables at a pressure of 20 bar,

$$t_{sat} = 212.4^\circ\text{C} + 273 = 485.4 \text{ K}$$

$$v_g = 0.1 \text{ m}^3/\text{kg}$$

We know that, the superheated steam obeys Charles's law ⑦

$$\frac{v_g}{T_{sat}} = \frac{v_{sup}}{T_{sup}}$$

$$v_{sup} = \frac{v_g}{T_{sat}} \times T_{sup} = \frac{0.1}{485.4} \times 573 = 0.118 \text{ m}^3/\text{kg} \checkmark$$

PROB. A boiler is supplied with feed water at a pressure of 4.5 bar. The water is converted into steam at a pressure of 5.5 bar and a temperature of 188°C. Determine the quantity of heat supplied per kg of steam.

SOL. At a pressure of 5.5 bar, $T_{sat} = 155.5^\circ\text{C}$
 $h_g = 2751.7 \text{ kJ/kg}$, $T_{sup} = 188^\circ\text{C}$ higher than saturation temperature
 \therefore since the given temp of steam (188°C) higher than saturation temperature
 $h_{sup} = h_g + C_p [T_{sup} - T_{sat}] = 2751.7 + 2.1 [188 - 155.5] = 2820 \text{ kJ/kg}$
 Since, water is supplied at 4.5 bar, the heat in feed water = $4.2 \times 45 = 189 \text{ kJ}$.
 \therefore Heat actually required = $2820 - 189 = 2631 \text{ kJ/kg} \checkmark$

Internal energy of steam:-

It is the actual heat energy stored in steam, above freezing point of water

For wet steam, internal energy of steam = Entropy @ total heat - External work done during evaporation

$$u = h - 100 p v_g \text{ --- (1) wet steam}$$

$$u = h_g - 100 p v_g \text{ --- (2) dry}$$

$$u = h_g + h_{sup} - 100 p v_{sup} \text{ --- (3) superheated.}$$

PROB. Calculate the internal energy of 1 kg of steam at a pressure of 10 bar when the steam is (a) 0.9 dry (b) dry saturated.
 From steam tables, corresponding to a pressure of 10 bar,

$$h_f = 762.6 \text{ kJ/kg}; h_{fg} = 2013.6 \text{ kJ/kg}; v_g = 0.1943 \text{ m}^3/\text{kg}$$

(a) internal energy of 1 kg of steam when it is 0.9 dry ($x = 0.9$)

$$u = h_f + x h_{fg} - 100 p x v_g = 762.6 + 0.9 \times 2013.6 - 100 \times 0.9 \times 0.1943$$

$$= 2400 \text{ kJ} \checkmark$$

(b) internal energy of 1 kg of steam when it is dry saturated

$$u = h_f + h_{fg} - 100 p v_g = 762.6 + 2013.6 - 100 \times 10 \times 0.1943 = 2581.9 \text{ kJ}$$

PROB steam at 18 bar and dryness 0.9 is heated at constant pressure until dry and saturated. Find the increase in volume, heat supplied and work done per kg of steam.

If the volume is kept constant, find how much heat must be extracted to reduce the pressure to 14 bar.

SOL Given, $p = 18 \text{ bar}$; $x = 0.9$; $p_1 = 14 \text{ bar}$.

From steam tables corresponding to a pressure of 18 bar, we find
 $h_f = 884.5 \text{ kJ/kg}$, $h_{fg} = 1910.3 \text{ kJ/kg}$; $h_g = 2794.8 \text{ kJ/kg}$
 $v_g = 0.1103 \text{ m}^3/\text{kg}$.

Increase in volume
= Volume of dry steam - Volume of wet steam
 $= v_g - x \times v_g = 0.1103 - 0.9 \times 0.1103 = 0.011 \text{ m}^3/\text{kg}$.

Increase in Heat Supplied
 $= h_g - h_{wet} = 2794.8 - [h_f + x \times h_{fg}]$
 $= 2794.8 - [884.5 + 0.9 \times 1910.3] = 2191 \text{ kJ/kg}$.

Increase in Work done
 $= 100 p [v_g - x v_g] = 100 \times 18 [0.1103 - 0.9993] = 19.8 \text{ kJ/kg}$

Heat extracted to reduce the pressure to 14 bar

During constant volume process, no work is done and extraction of heat will result in the reduction of internal energy of steam.

From steam tables, corresponding to a pressure of 14 bar,
 $h_{f1} = 830.1 \text{ kJ/kg}$, $h_{fg1} = 1957.7 \text{ kJ/kg}$; $v_{g1} = 0.1407 \text{ m}^3/\text{kg}$.
 $x_1 =$ Dryness fraction of steam

Since the volume is constant,
 $v_g = x_1 v_{g1}$ $\therefore x_1 = \frac{v_g}{v_{g1}} = \frac{0.1103}{0.1407} = 0.78$

Now, internal energy of steam at a pressure of 18 bar,
 $u = h_g - 100 p v_g = 2794.8 - 100 \times 18 \times 0.1103 = 2596.3 \text{ kJ/kg}$

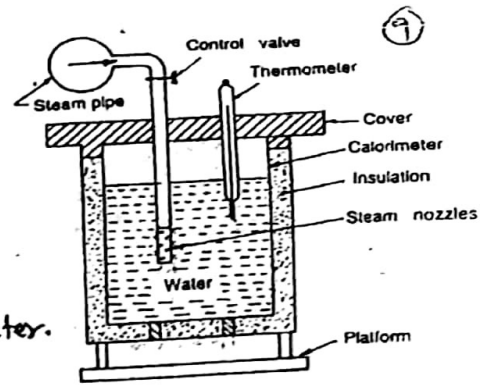
internal energy of steam at a pressure of 14 bar,
 $u_1 = h_{f1} + x_1 h_{fg1} - 100 p_1 x_1 v_{g1}$
 $= 830.1 + 0.78 \times 1957.7 - 100 \times 14 \times 0.78 \times 0.1407$
 $= 2203 \text{ kJ/kg}$.

Heat extracted to reduce pressure $= u - u_1 = 2596.3 - 2203 = 393.3 \text{ kJ/kg}$

* Barrel calorimeter

In barrel calorimeter, the known mass of steam sample and of known pressure is condensed by mixing it with a known mass of cold water. The steam condenses into water, thereby increasing the mass and temperature of the water in the calorimeter.

The heat supplied by the condensing steam is determined, with the help of the initial and final temperatures of the water and calorimeter.



Barrel calorimeter.

Let p = pressure of the steam in bar

t = Temp. of steam formed

h_{fg} = latent heat of steam at pressure p (from steam tables)

m_c = mass of the calorimeter.

c_c = specific heat of the calorimeter.

m_{ce} = water equivalent of the calorimeter = $m_c \times c_c$.

m_s = mass of steam condensed

m_w = mass of cold water in calorimeter.

t_1 = initial temp. of water and calorimeter

t_2 = final temp. of water and calorimeter

c_w = specific heat of water

x = dryness fraction of steam sample.

According to law of conservation of energy, heat lost by steam is equal to heat gained by water and calorimeter.

$$m_s [x h_{fg} + c_w (t - t_1)] = (m_w c_w + m_c c_c) (t_2 - t_1)$$

From this expression, the dryness fraction of steam (x) may be determined.

Prob In a laboratory experiment on wet steam by a barrel calorimeter, the following observations were recorded.

Mass of copper calorimeter = 1 kg

Mass of Calorimeter + water = 3.8 kg

Mass of Calorimeter + water + steam = 4 kg

Initial temperature of water = 10°C

Final temperature of water = 50°C

Steam pressure = 5.5 bar

If the specific heat of copper is 0.406 kJ/kgK, determine dryness fraction of steam.

Sol: Mass of steam, $m_s = (4 - 3.8) = 0.2$ kgs.

From steam tables, corresponding to a pressure of 5.5 bar,

$t = 155.5^\circ\text{C}$, $h_{fg} = 2095.5$ kJ/kg.

x = Dryness fraction of steam.

According to law of conservation of energy, (10)
 Heat lost by steam = Heat gained by water
 $m_s [x \cdot h_{fg} + c_w (t - t_2)] = [m_w c_w + c_c m_c] (t_2 - t_1)$
 $0.2 [x \cdot 2095.5 + 4.2 (155.5 - 50)] = (2.8 \times 4.2 + 1 \times 0.406) (50 - 10)$

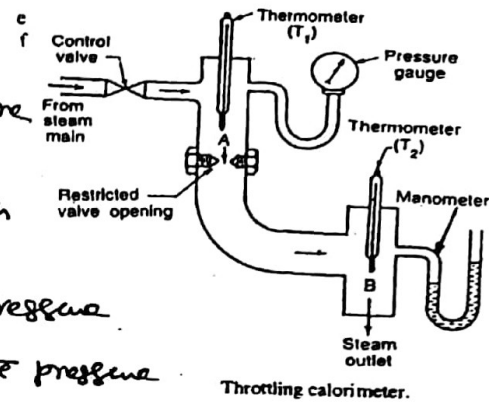
Dryness fraction, $x = 0.95$ ✓

Throttling calorimeter

A throttling calorimeter used to determine the dryness fraction of steam.

It consists of a separator A into which steam is admitted through a control valve from the steam main. The pressure and temperature are measured by the pressure gauge and the thermometer T_1 provided in this section.

The steam is then throttled through a narrow aperture of restricted valve openings, its total heat remaining constant. The steam is in superheated state after throttling at a lower pressure than previous. The temperature and pressure of steam leaving the calorimeter B is noted by thermometer T_2 and manometer respectively.



Total heat before throttling = total heat after throttling

At pressure p_1 , $h_{f1} + x h_{fg1} = h_{g2} + c_p [t_{sup} - t_{sat2}]$. At pressure p_2 .

PROB. On a throttling calorimeter, the steam is admitted at a pressure of 10 bar. If it is discharged at atmospheric pressure and 110°C after throttling, determine the dryness fraction of steam. Assume, specific heat of steam = 2.2 kJ/kgK .

SOL. $p_1 = 10 \text{ bar}$; $p_2 = 1.013 \text{ bar}$; $t_{sup} = 110^\circ\text{C}$; $c_p = 2.2 \text{ kJ/kgK}$
 $x =$ Dryness fraction of steam.

From steam tables, corresponding to a pressure of 10 bar,
 $h_{f1} = 762.6 \text{ kJ/kg}$; $h_{fg1} = 2013.6 \text{ kJ/kg}$.

and corresponding to a pressure of 1.013 bar,
 $h_{g2} = 2676 \text{ kJ/kg}$; $t_{sat2} = 100^\circ\text{C}$

\therefore we have, $h_{f1} + x h_{fg1} = h_{g2} + c_p [t_{sup} - t_{sat2}]$

$762.6 + x \cdot 2013.6 = 2676 + 2.2 (110 - 100)$

Dryness fraction $\therefore x = \frac{2698 - 762.6}{2013.6} = 0.961$ ✓

Separating Calorimeter

The separating calorimeter is used to determine the dryness fraction of steam by mechanically separating the water particles from the wet steam.

The wet steam enters at the top of the calorimeter through a control valve. It strikes the perforated cup and thereby quick reversal of direction of motion. The water particles due to their greater moment of inertia tend to move on, and consequently get separated from the mixture. The separated water gets collected at the bottom of the inner chamber.

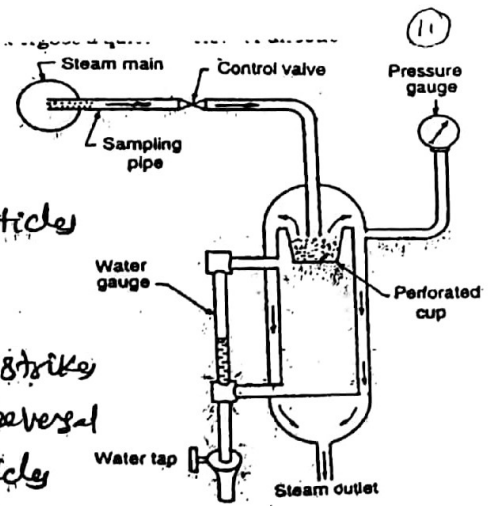


Fig. 30. Separating calorimeter.

The amount of dry steam leaving at the outer chamber of the calorimeter may be measured by condensing it in a weighed quantity of cold water.

Let m = Mass of water collected in a certain time
 M = Mass of dry steam passing in the same time
 x = Dryness fraction of wet steam.

$$\therefore \text{Dryness fraction, } x = \frac{\text{Mass of dry steam}}{\text{Mass of dry steam} + \text{Mass of water}}$$

$$x = \frac{M}{M+m}$$

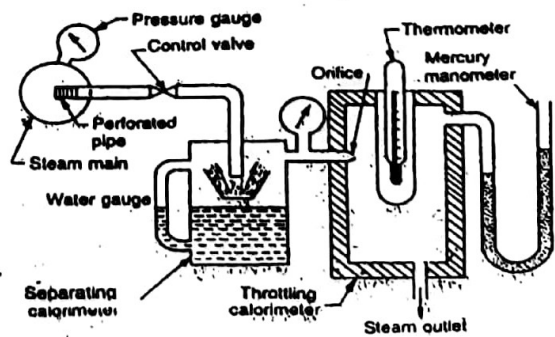
Combined Separating & Throttling Calorimeter

In this calorimeter, the wet steam is first collected in a perforated collecting pipe and then passed through a separating calorimeter.

A part of the water is removed by a separating calorimeter owing to quick change of direction of flow.

The resulting semi-dry steam is throttled in to a throttling calorimeter. This method ensures that the steam will be superheating after throttling.

Let x_1 = Dryness fraction of steam considering separating calorimeter
 x_2 = Dryness fraction of steam entering the throttling calorimeter
 Actual dryness fraction of steam in the steam main $x = x_1 \times x_2$



Combined separating and throttling calorimeter.

¹²
Entropy of steam: The entropy of steam is also an important property, which increases with the addition of heat and decreases with its removal.

The ~~increase~~ entropy of steam consists of

1. Increase in entropy of water during heating from freezing point to boiling point corresponding to pressure at which water is being heated
2. Increase in entropy during evaporation
3. Increase in entropy during superheating.

Entropy of wet steam:- $S_f + x \frac{h_{fg}}{T} = S_f + x \cdot S_{fg}$

Entropy of dry steam:- $S_f + S_{fg} = S_g$

Entropy of superheated steam:- $S_g + c_p \ln \frac{T_{sup}}{T_{sat}}$

PROB. Find the entropy of 1 kg of dry saturated steam at a pressure of 5.2 bar. The boiling point of water at this pressure is given as 152.6 °C and its total heat at this temperature is 2110 kJ/kg.

SOL. The value of entropy of dry saturated steam (S_g) may be directly read from steam tables corresponding to a pressure of 5.2 bar.

From steam table at 5.2 bar; $S_f = 1.86 \text{ kJ/kgK}$
 $S_{fg} = 4.96 \text{ kJ/kgK}$

$\therefore S_g = S_f + S_{fg} = 1.86 + 4.96 = 6.82 \text{ kJ/kgK}$ ✓

PROB. Calculate entropy of 1 kg of wet steam with dryness fraction of 0.9 at a pressure of 8.4 bar.

SOL. From steam tables at 8.4 bar,
 $S_f = 2.066 \text{ kJ/kgK}$; $S_{fg} = 4.577 \text{ kJ/kgK}$.

\therefore Entropy of 1 kg of wet steam, $S = S_f + x S_{fg} = 2.066 + 0.9 \times 4.577 = 6.186 \text{ kJ/kgK}$.

PROB. Determine the entropy of per kg of superheated steam at a pressure of 20 bar and a temp. of 250 °C. Assume c_p for superheated steam as 2.2 kJ/kgK.

SOL. $p = 20 \text{ bar}$; $T_{sup} = 250^\circ\text{C} = 250 + 273 = 523 \text{ K}$; $c_p = 2.2 \text{ kJ/kgK}$.

From steam tables, corresponding to 20 bar pressure,
 $T = 212.4^\circ\text{C} = 212.4 + 273 = 485.4 \text{ K}$ $S_g = 6.337 \text{ kJ/kgK}$.

Entropy of 1 kg of superheated steam

$S_{sup} = S_g + c_p \ln \frac{T_{sup}}{T_{sat}} = 6.337 + 2.2 \ln \frac{523}{485.4} = 6.5 \text{ kJ/kgK}$ ✓

UNIT-4

Vapour processes:- The following steps are suggested to solve Vapour process problems:-

- ① Find final condition of steam; $v_{wet_2} = x \cdot v_{g_2}$ (or) $v_{dry_2} = v_{g_2}$ (or) $v_{sup_2} = T_{sat_2} \times \frac{v_g}{T_{sat}}$
- ② Change in internal energy, $u_2 - u_1 = h_{f_2} - 100 \cdot h_{f_1} - (h_1 - 100 \cdot h_{f_1})$
 $[h_{wet} = h_f + x \cdot h_{fg}; h_{dry} = h_f + h_{fg} = h_g; h_{sup} = h_g + c_{ps} [T_{sup} - T_{sat}]$
- ③ Work done, $W_{1-2} = \int p dv$

$W_{1-2} = 0$	$W_{1-2} = p_2 (v_2 - v_1)$	$W_{1-2} = p_1 v_1 \ln \frac{v_2}{v_1}$	$W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1}$	$W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1}$
const. volume	const. pressure	isothermal	polytropic	adiabatic
- ④ obtain Heat transfer, $Q_{1-2} = m(u_2 - u_1) + W_{1-2}$.

① Constant volume process

consider 1 kg of wet steam at pressure p_1 , dryness fraction x_1 , heated to pressure p_2 at const. vol. since, volume is constant

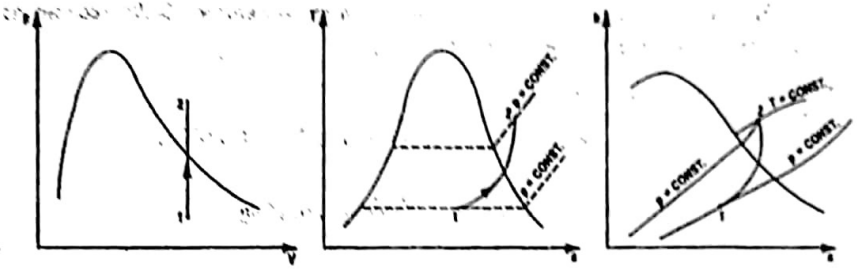


Fig. 7.12 Constant Volume Process

$x_1 v_{g1} = x_2 v_{g2} \Rightarrow x_2 = \frac{x_1 v_{g1}}{v_{g2}}$; if $x_2 < 1$, then final state is superheated.

② $u_2 - u_1 = (h_2 - 100 \cdot h_{f_2}) - (h_1 - 100 \cdot h_{f_1})$

③ $W_{1-2} = 0$; ④ $Q_{1-2} = (u_2 - u_1) + 0 = (u_2 - u_1)$

PROB- The steam contained in a closed vessel of fixed volume 0.14 m^3 , exerts a pressure of 10 bar at 250°C . If the vessel is cooled to pressure falls to 3.5 bar, determine the heat transfer and change in entropy.

SOL: From steam tables At pressure $p_1 = 10 \text{ bar}$; $T_{sat_1} = 133.9^\circ\text{C}$, so the superheated steam temp is 250°C which is more than T_{sat_1} .

\therefore At 10 bar and 250°C ; $v_{sup_1} = 0.2238 \text{ m}^3/\text{kg}$; $h_{sup_1} = 2943 \text{ kJ/kg}$; $s_1 = 6.926 \text{ kJ/kgK}$.

mass of steam in the vessel, $m = \frac{V}{v_{sup_1}} = \frac{0.14}{0.2238} = 0.6214 \text{ kg}$.

At: 3.5 bar (p_2); $h_{f_2} = 584.3 \text{ kJ/kg}$; $h_{fg_2} = 2147.3 \text{ kJ/kg}$; $v_{g_2} = 0.5237 \text{ m}^3/\text{kg}$

$s_{f_2} = 1.727 \text{ kJ/kgK}$; $s_{fg_2} = 5.212 \text{ kJ/kgK}$.

Final state dryness fraction $v_{sup_2} = x_2 v_{g_2} \Rightarrow x_2 = \frac{v_{sup_1}}{v_{g_2}} = \frac{0.2238}{0.5237} = 0.4273$ (wet).

\therefore Change in entropy = $[h_2 - 100 \cdot h_{f_2}] - [h_1 - 100 \cdot h_{f_1}] = [h_2 + x_2 h_{fg_2} - 100 \cdot h_{f_2}] - [h_{sup_1} - 100 \cdot h_{f_1}]$
 $= [584.3 + 0.4273 \times 2147.3] - [100 \times 3.5 \times 0.4273 \times 0.5237] - [2943 - 100 \times 10 \times 0.2238]$
 $= 1456.58 \text{ kJ/kg} - 2710.2 \text{ kJ/kg}$
 $= -1253.62 \text{ kJ/kg}$

$$\therefore \text{Heat Transfer, } Q_{1-2} = m \cdot [u_2 - u_1] \\ = 0.6014 [1253.34] = -753.76 \text{ kJ}$$

$$\text{change in entropy, } S_2 - S_1 = m \cdot \left[(S_{f2} + x_2 \cdot S_{fg2}) - (S_{f1} + x_1 \cdot S_{fg1}) \right] \\ = 0.6014 \left[(1.727 + 0.4443(5.212)) - (6.926) \right] \\ = -0.6014 \times 2.883 = -1.734 \text{ kJ/K}$$

Constant pressure process:-

Consider 1 kg of steam with dryness fraction, heated at constant pressure to final condition 2.

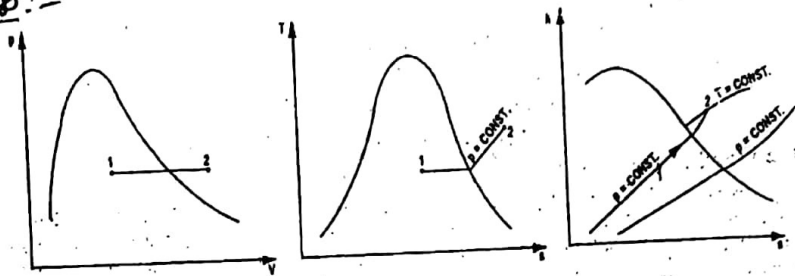


Fig. 7.13 Constant Pressure Process

- ② $W_{1-2} = \text{Workdone} = p_2 [v_2 - v_1]$
- ③ change in internal energy, $(u_2 - u_1) = (h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$
- ④ Heat transfer, $Q_{1-2} = W + (u_2 - u_1) = (h_2 - h_1)$.

PROB. one kg of steam at pressure of 20 bar and dryness fraction 0.85 is heated at a constant pressure to 300°C. Determine (a) Heat transferred (b) workdone (c) change in internal energy.

SOL. At 20 bar, $t_g \neq t_{sat} = 212.4^\circ\text{C}$. The final condition (state 2) is superheated with a temperature of 300°C.

$$\text{At 20 bar, } h_f = 908.6 \text{ kJ/kg; } h_{fg} = 1888.7 \text{ kJ/kg} \\ v_{g1} = 0.099549 \text{ m}^3/\text{kg} \\ h_1 = h_{wet1} = h_f + x_1 h_{fg} = 908.6 + 0.85(1888.7) \\ = 2514 \text{ kJ/kg}$$

and final condition (state 2)

At 20 bar ($p_1 = p_2$) and 300°C (t_{sup})

$$h_2 = 3025 \text{ kJ/kg; } v_2 = v_{sup2} = 0.1255 \text{ m}^3/\text{kg}$$

$$\therefore \text{Heat transfer, } Q_{1-2} = (h_2 - h_1) = 3025 - 2514 = 511 \text{ kJ/kg}$$

$$\text{workdone, } W_{1-2} = 10^5 [p_2 v_2 - p_1 v_1] = 10^5 [20 \times 0.1255 - 0.85 \times 0.09954] \\ = 81.767 \text{ kJ/kg}$$

$$\therefore \text{change in internal energy, } (u_2 - u_1) = Q - W = 511 - 81.767 \\ = 429.23 \text{ kJ/kg}$$

Constant temperature process

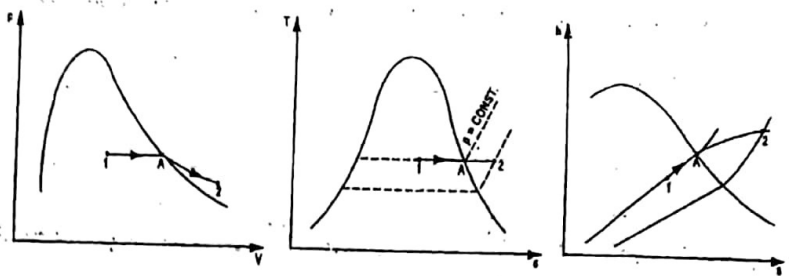


Fig. 7.14 Isothermal Process

isothermal (constant temperature process):

consider 1 kg of steam expands from state 1 to 2 isothermally.

The law of governing isothermal process: $p_1 v_1 = p_2 v_2$
 $p_1 (x_1 v_{g1}) = p_2 (x_2 v_{g2})$

if $x_2 = \text{less than } 1$; $v_2 = x_2 v_{g2}$

if $x_2 > 1$; $v_{sup2} = T_{sup2} \times \frac{v_{g2}}{T_{sat2}} = v_2$

$\therefore W_{1-2} = p_1 v_1 \ln \frac{v_2}{v_1}$

$u_2 - u_1 = (h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$

$\therefore Q = W + (u_2 - u_1)$ &

PROB. A quantity of dry saturated steam occupies 0.2634 m^3 at 15 bar. Determine the final condition of steam if it is compressed until the volume is halved. If the compression is carried out in an isothermal manner, determine heat rejection during the compression.

SOL. At 15 bar, $v_g = 0.1317 \text{ m}^3/\text{kg}$ $h_f = 844.7 \text{ kJ/kg}$
 dry saturated ($x=1$) $h_{fg} = 1945 \text{ kJ/kg}$ $h_g = 2789 \text{ kJ/kg}$.

mass of steam, $m = \frac{V}{v_g} = \frac{0.2634}{0.1317} = 2 \text{ kg}$.

Final condition; $v_2 = \frac{v_1}{2} = \frac{0.1317}{2} = 0.0659 \text{ m}^3/\text{kg}$.

Condition:- since the steam is in wet region; the pressure also remains constant [for wet steam, $P \& T$ are constant].

$x_2 \cdot v_{g2} = v_2 \Rightarrow x_2 = \frac{0.0659}{0.1317} = 0.5$

$h_2 = h_{f2} + x_2 \cdot h_{fg2} = 844.7 + 0.5(1945.2) = 1817 \text{ kJ/kg}$

\therefore Heat transferred, $Q = m [h_2 - h_1] = 2 [1817.3 - 2789.9]$
 $= -1945.2 \text{ kJ}$ [Heat rejection]

polytropic process: -

polytropic process is given by

$$pV^n = \text{constant}$$

For polytropic expansion

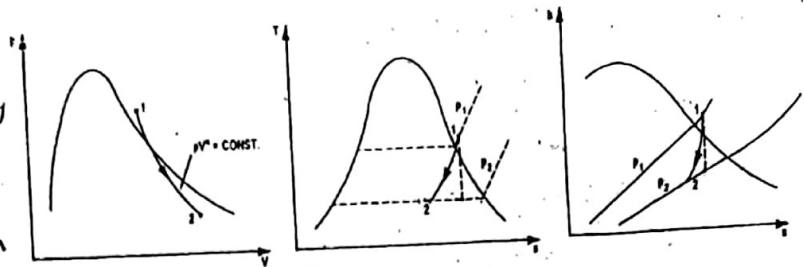


Fig. 7.16 polytropic process

$$\Rightarrow x_2 = \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}} \cdot \frac{x_1 v_{g1}}{v_{g2}}$$

$$\text{If } x_2 < 1; v_2 = x_2 \cdot v_{g2}$$

$$\text{If } x_2 > 1; v_2 = T_{sup} x_2 \cdot \frac{v_{g2}}{T_{sat}}$$

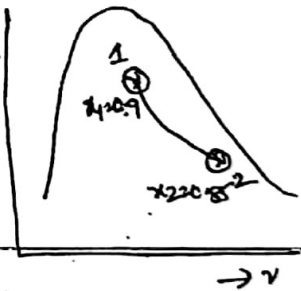
$$\therefore W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{n-1}$$

$$Q_{1-2} = (u_2 - u_1) + W; (u_2 - u_1) = (h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$$

PROB: Steam at 3 bar and 0.9 dry expands in a cylinder till the volume is 4 times at the beginning. The law of expansion is $pV^{1.1} = \text{constant}$. Find the change in internal energy, work done and steam condition at the end of the process.

Sol: From steam tables at $p_1 = 3 \text{ bar}$ $h_{f1} = 561.4 \text{ kJ/kg}$, $h_{g1} = 2163 \text{ kJ/kg}$
The specific volume of vapour, $v_{g1} = 0.6058 \text{ m}^3/\text{kg}$.

$$\therefore \text{Initial volume, } v_1 = x_1 v_{g1} = 0.9 \times 0.6058 = 0.545 \text{ m}^3/\text{kg}$$



$$\text{Final volume, } v_2 = 4 \cdot v_1 = 4 \times 0.545 = 2.18 \text{ m}^3/\text{kg}$$

$$\text{According to law of expansion, } p_1 v_1^{1.1} = p_2 v_2^{1.1} \Rightarrow p_2 = p_1 \left(\frac{v_1}{v_2}\right)^{1.1}$$

$$\text{Find pressure. } \therefore p_2 = 3 \left[\frac{1}{4}\right]^{1.1} = 0.6529 \text{ bar}$$

$$\therefore \text{we know the value, } v_2 = 2.18 \text{ m}^3/\text{kg}$$

From steam tables, find value, At $p_2 = 0.652 \text{ bar}$, $v_{g2} = 2.548 \text{ m}^3/\text{kg}$.

$$\text{To find final condition of steam. } v_2 = x_2 \cdot v_{g2}; \Rightarrow 2.18 = x_2 \times 2.548 \Rightarrow x_2 = 0.85$$

$$\therefore \text{At } p_2 = 0.652 \text{ bar; } h_{f2} = 368 \text{ kJ/kg; } h_{g2} = 2492 \text{ kJ/kg}$$

$$\therefore \text{initial enthalpy; } h_1 = h_{f1} + x_1 h_{fg1} = 561.4 + 0.9 \times 2163 = 2508 \text{ kJ/kg}$$

$$h_2 = h_{f2} + x_2 h_{fg2} = 368 + 0.85 \times 2492 = 2486 \text{ kJ/kg}$$

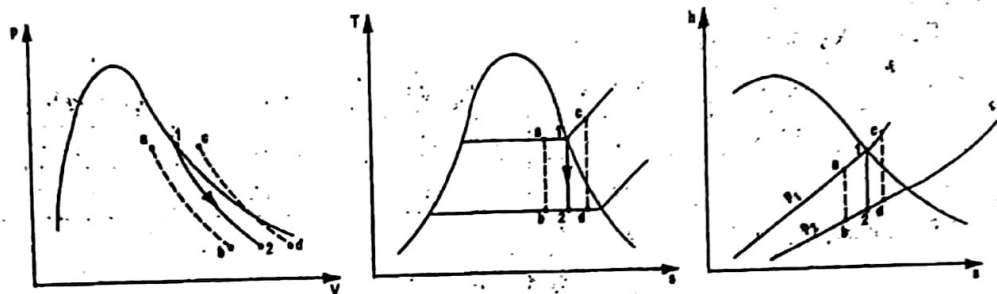
$$\text{change in internal energy } (u_2 - u_1) = (h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$$

$$= (2486 - 100 \times 0.652 \times 2.18) - (2508 - 100 \times 3 \times 0.545)$$

$$\text{Work done, } W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{n-1} = \frac{(100 \times 3 \times 0.545 - 10 - 65 \times 2.18)}{1-1}$$

$$= 218 \text{ kJ/kg}$$

Adiabatic process [Isentropic process] :-



In Adiabatic process, no heat transfer takes place, but work is done due to expense of internal energy. As there is no heat transfer, entropy remains constant. Therefore, adiabatic process is also referred as isentropic process. It is represented by vertical line on $h-s$ and $T-s$ diagrams.

Consider 1 kg of steam expands isentropically from p_1 to p_2 .

Entropy before expansion = Entropy after expansion; $S_1 = S_2$

For Adiabatic process, $p_1 v_1^n = p_2 v_2^n$; $W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{n-1}$

$n \rightarrow 1.13$ for wet steam

1.3 for superheated steam

1.35 for dry steam

$$Q_{1-2} = 0$$

PROB. 4 kg of steam expands adiabatically from 16 bar and 250°C to 0.6 bar in a steam turbine such that steam is dry and saturated at the end of expansion. Calculate work done by steam.

From superheated steam table At $p_1 = 16 \text{ bar}$ & $t_{sup} = 250^\circ\text{C}$

$$v_1 = v_{sup} = 0.1483 \text{ m}^3/\text{kg}$$

For superheated steam initially $p_1 v_1^{1.3} = p_2 v_2^{1.3}$ [$n=1.3$ for superheated steam]

$$\Rightarrow v_2 = v_1 \left[\frac{p_1}{p_2} \right]^{1/1.3} = 0.1483 \left[\frac{16}{0.6} \right]^{1/1.3} = 0.1483 [26.6]^{0.769} = 1.85 \text{ m}^3/\text{kg}$$

$$\therefore \text{Work done, } W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{n-1} = \frac{100 [16 \times 0.1483 - 0.6 \times 1.85]}{1.3-1} = 420.9 \text{ kJ/kg}$$

$$\text{For 4 kg; } W_{1-2} = 4 \times 420.9 = 1683 \text{ kJ/kg}$$

Throttling process :-

Flow of fluid through a restricted passage causes pressure drop is called throttling process. For example, flow through partially opened valve, capillary tube and porous plug is regarded as throttling process.

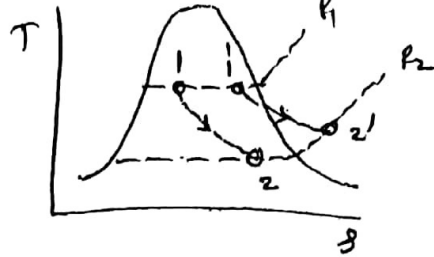
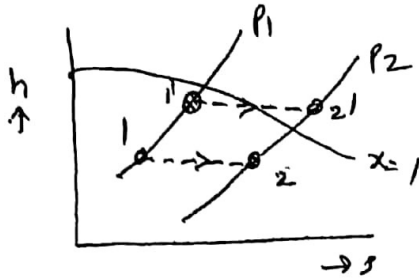
During throttling process, Enthalpy remains constant, but quality of steam is improved due to internal friction.

For throttling process, $h_1 = h_2$

$$h_1 + x_1 h_{fg1} = h_2 + x_2 h_{fg2}$$

For binodal condition is superheated,

$$h_{f1} + x_1 h_{fg1} = h_{g2} + c_p [t_{sup2} - t_{sat2}]$$



PROB. Steam initially at a pressure of 10.5 bar and 0.96 dry throttled at a pressure of 1 bar. Find final condition of steam. Also calculate change in entropy per kg of steam.

P bar	$t_{sat}, ^\circ C$	$h_f, \text{KJ/kg}$	$h_{fg}, \text{KJ/kg}$	$h_g, \text{KJ/kg}$	$S_f, \text{KJ/kgK}$	$S_g, \text{KJ/kgK}$
10.5	182	772.0	2006	-	2.159	6.566
1	99.63	-	-	2675.4	-	7.36

Take c_p for superheated steam = 2.1 KJ/kgK.

SOL

For, Throttling process

$$h_{f1} + x_1 h_{fg1} = h_{g2} + c_p (t_{sup2} - t_{sat2})$$

$$772 + 0.96 (2006) = 2675 + 2.1 (t_{sup2} - 99.63)$$

$$t_{sup2} = 110.27^\circ C$$

Entropy at 10.5 bar and 0.96 dry

$$S_1 = S_{f1} + x_1 S_{fg1} = S_{f1} + x_1 (S_{g1} - S_{f1})$$

$$= 2.159 + 0.96 (6.566 - 2.159) = 6.3897 \text{ KJ/kgK}$$

Entropy at 1 bar and 110.27°C

$$S_2 = S_{g2} + c_p \ln \frac{T_{sup2}}{T_{sat2}} = 7.36 + 2.1 \ln \left(\frac{110.27 + 273}{99.63 + 273} \right)$$

$$= 7.419 \text{ KJ/kgK}$$

$$\therefore \text{Change in Entropy, } S_2 - S_1 = 7.419 - 6.3897 = 1.0293 \text{ KJ/kgK}$$

+