Mass Transfer Operations I

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Module - 4
Absorption
Lecture - 1
Introduction to Absorption and solvent selection

Welcome to the first lecture of module 4 which is on absorption. In earlier modules, in module 2 which we have discussed, the mass transfer coefficient concepts, and where we have discussed the interphase mass transfer among the phases and their equilibrium relationship between the phases for transfer of gaseous components into the liquids. Module 3 we have discussed the equipment, which is generally used for gas liquid operations. So, here today, we will discuss the absorption of gases into the liquids.

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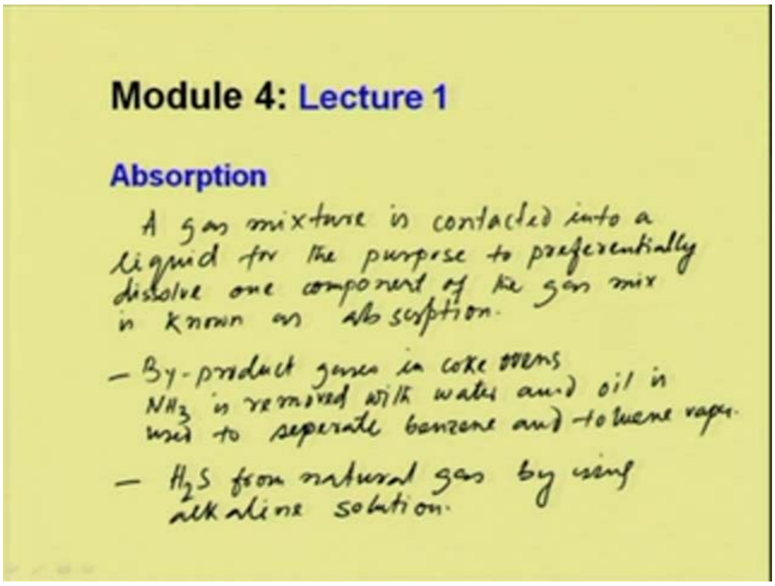

Module 4: Lecture 1

Absorption

A gas mixture is contacted into a liquid for the purpose to preferentially dissolve one component of the gas mix is known as absorption.

- By-product gases in coke ovens NH_3 is removed with water and oil is used to seperate benzene and toluene vapor.
- H_2S from natural gas by using alkaline solution.

When a gas mixture is contacted into a liquid for the purpose to preferentially dissolve one component of the gas mixture is known as absorption. For example, if we take by product gases in coke ovens where ammonia is removed with water and then oil is used to separate benzene and toluene vapor. So, another example is like we remove for hydrogen sulfide from natural gas H2S which is very much objectionable from natural gas by using alkaline solution.

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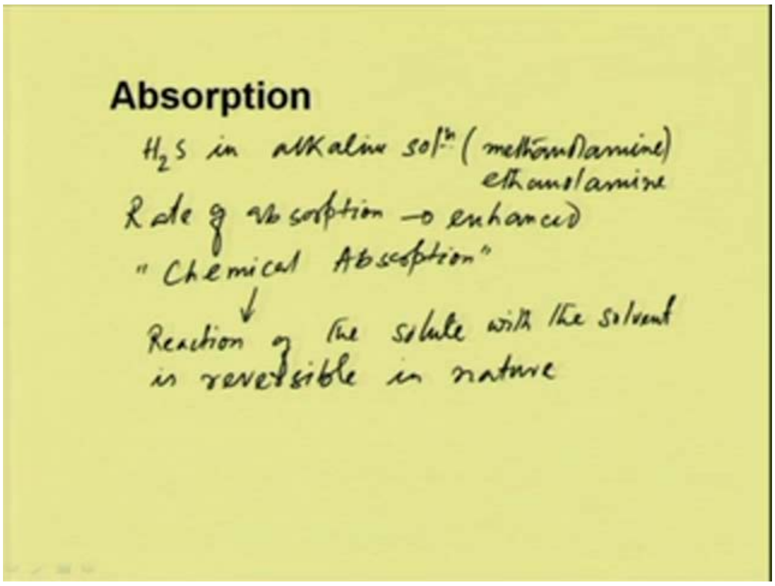

Absorption

H_2S in alkaline sol^{n} (methanolamine)
ethanolamine

Rate of absorption → enhanced

"Chemical Absorption"

↓

Reaction of the solute with the solvent
is reversible in nature

So, as we said in the second example if we absorb hydrogen sulfide in alkaline solutions, the solvent reacts with the solute hydrogen sulfide. So, chemical reactions takes place alkaline solution for example, methanol amine or ethyl amine or ethanol amine, these are the basic compounds we can use as alkaline solvent and hydrogen sulfide reacts. So, due to this chemical reactions the rate of absorption enhanced and the process is known as chemical absorption which is distinguished from the physical absorptions and in many situations it may happen that the solvent we which we used, we need to regenerate the solvent for reuse and we may need the absorbed solute for further use. So, in that case the reaction of the solute with the solvent is reversible in nature, which is preferred.

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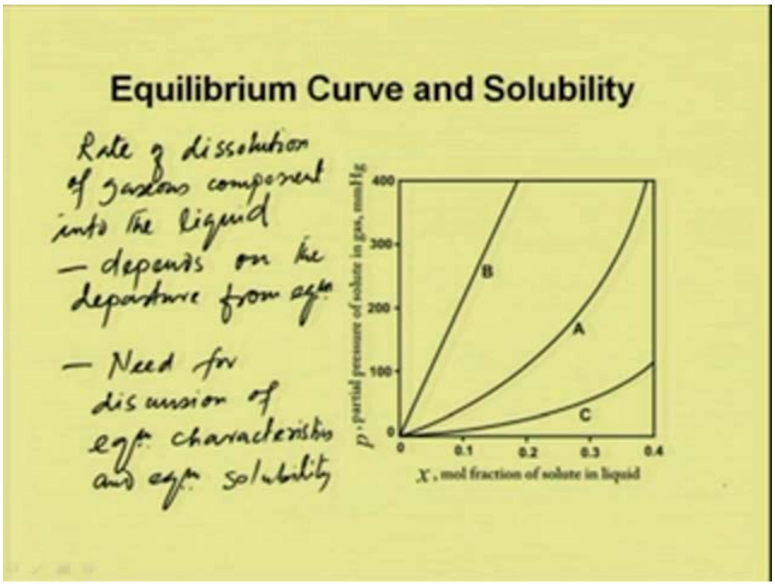
Equilibrium Curve and Solubility

Rate of dissolution of gaseous component into the liquid

— depends on the departure from eqm.

— Need for discussion of eqm. characteristics and eqm. solubility

So, rate of the dissolution of gaseous component into the liquid depends on the departure from equilibrium. So, it is necessary to discuss the equilibrium characteristics and the equilibrium solubility of the gaseous components into the liquid. So, need for discussion of equilibrium characteristics and equilibrium solubility.

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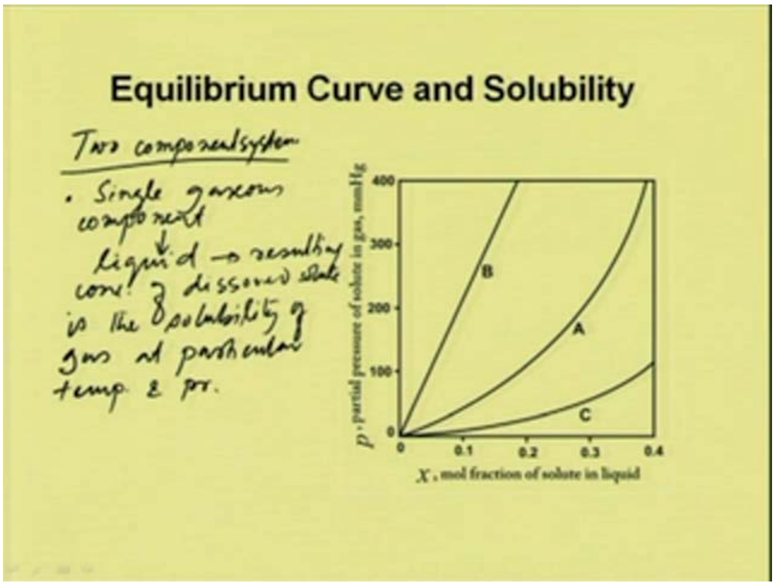
Equilibrium Curve and Solubility

Two component system

- Single gaseous component
  ↓
  liquid → resulting conc. of dissolved solute is the solubility of gas at particular temp. & pr.

So, let us consider two component system, that means we will take a single gaseous component in contact with the liquid and the resulting concentration of dissolve solute, solute is the solubility of gas at particular temperature and pressure. So, suppose at a fixed temperature if we look into this diagram at fixed temperature the solubility concentration increases with increasing partial pressure; as we can see from the figures A, B and C. So, these figures will different, different gases have different solubility into the liquid, when the solubility of a particular component the or the partial pressure of a particular component at a certain mole fractions in the liquid is low or the partial pressure is high at a lower mole fraction then we say that the gas is less soluble.

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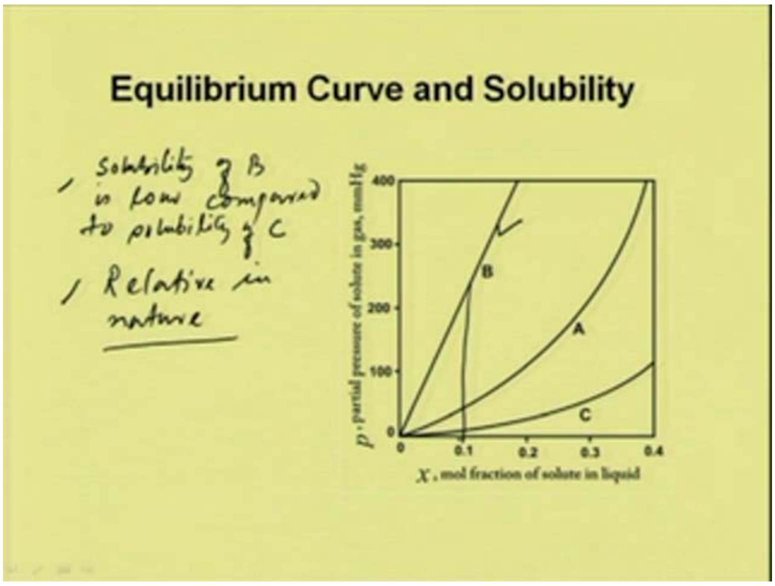

Equilibrium Curve and Solubility

✓ solubility of B
is low compared
to solubility of C

✓ Relative in
nature

Like if we see in case of B, the solubility of B is low compared to solubility of C at a particular partial pressure in the gas phase is low in case of C compared to B. That means the component C is more soluble in the liquid compared to solute B. Now, all these are the relative matters. So, this solubility are relative, that means if we apply the higher pressure and depending on our requirement we will able to solubilize the gaseous component into the liquid. So, all these are relative matters, but relative to different gases we can say that some gases as relatively insoluble compare to other gases.

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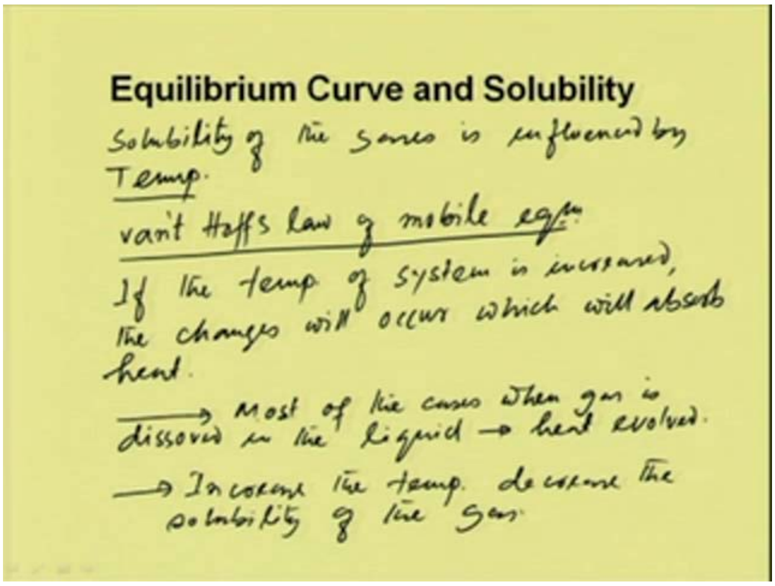

Equilibrium Curve and Solubility

Solubility of the gases is influenced by Temp.

vant Hoffs law of mobile eqm.

If the temp of system is increased, the changes will occur which will absorb heat.

→ Most of the cases when gas is dissolved in the liquid → heat evolved.

→ Increase the temp. decrease the solubility of the gas.

The solubility of the gases is influenced by temperature and it is follows Vant Hoffs law of mobile equilibrium. That means if the temperature of a system is increased, the changes will occur which will absorb heat. In most of the cases when gas is dissolved into the liquid then heat is evolved. That means if we increase the temperature which will decrease the solubility of the gaseous component. So, increase the temperature, decrease the solubility of the gas.

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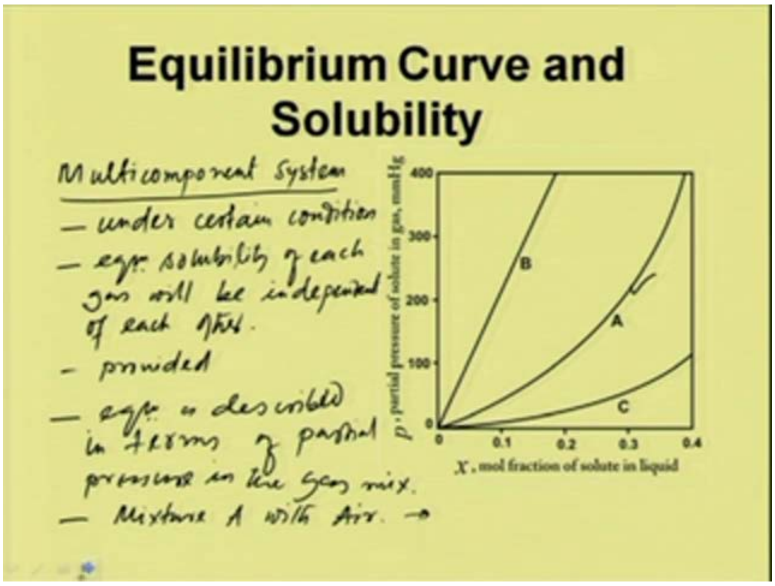

Equilibrium Curve and Solubility

Multicomponent System

- under certain condition
- eqm. solubility of each gas will be independent of each other.
- provided
- eqm. is described in terms of partial pressure in the gas mix.
- Mixture A with Air. →

Now, if we consider multi component system, so if we take a mixture of gaseous component and brought into contact with the liquid, then under certain conditions, condition equilibrium solubility of each gas will be independent of each other, provided the equilibrium is described in terms of partial pressure in the gas mixtures.

If all components, but one of the components are substantially insoluble in that case their concentration will be so small in the liquid phase, so that its solubility will not influence the solubility of the other components or the solubility of the generalization principle as we said which will not be influenced by the presence of other solutes will be applicable. That means if we take this is the solubility of component A at a particular temperature and pressure. If we take a mixture of A with air and so taking mixture A with air, so as long as we define or we plot in terms of the partial pressure of the component A in air, the air will not influence the solubility of component A.

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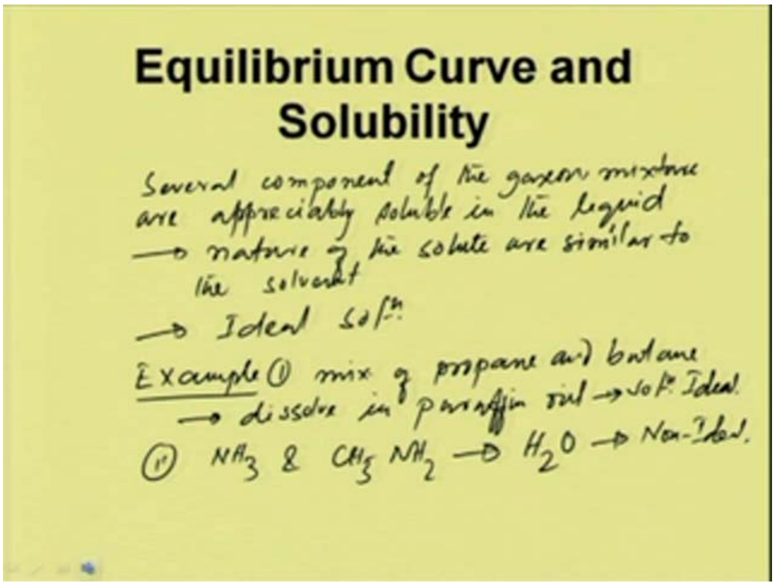

Equilibrium Curve and Solubility

Several component of the gaseous mixture are appreciably soluble in the liquid

→ nature of the solute are similar to the solvent

→ Ideal solⁿ

Example ① mix of propane and butane

→ dissolve in paraffin oil → solⁿ Ideal.

(ii) NH_3 & CH_3NH_2 → H_2O → Non-Ideal.

If several components are appreciably soluble, component of the mixture are appreciably soluble in the liquid, then this generalization will only applies when the nature of the solute are similar to the solvent. Nature of the solute are similar to the solvent; that means for ideal solution. For example, if we take a mixture of propane and butane and dissolve in non-volatile paraffin oil, then the solution is ideal, but if we take ammonia and methylamine and dissolve in water, then the it is expected that the methylamine can influence the solubility of ammonia in the solutions because the solution is non-ideal.

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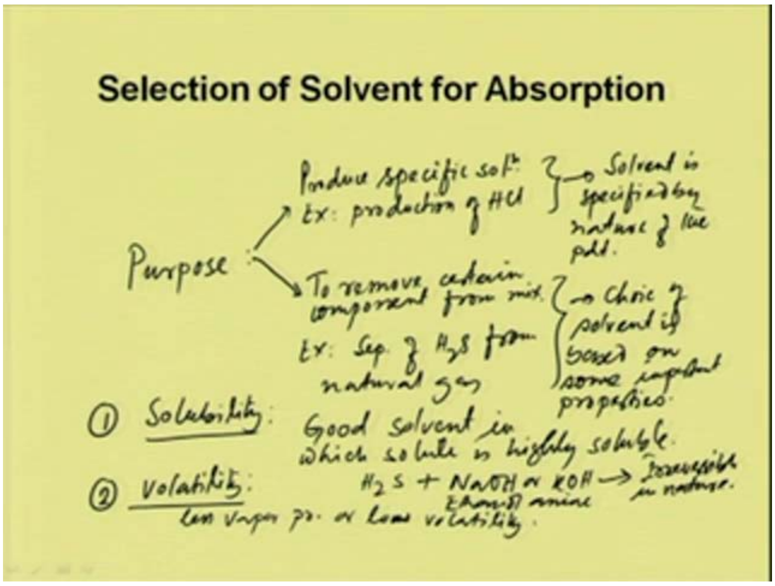

Selection of Solvent for Absorption

Purpose:
- Produce specific sol^n / Ex: production of HCl } → Solvent is specified by nature of the pdt.
- To remove certain component from mix. / Ex: Sep. of H_2S from natural gas } → Choice of solvent is based on some important properties.

① Solubility: Good solvent in which solute is highly soluble.

② Volatility: H_2S + NaOH or KOH → irreversible in nature. / Ethanol amine

Low vapor pr. or low volatility.

Now, we will discuss how we can select a solvent for particular absorption operations. So, the solvent can be identified based on the purpose of use. So, if the purpose is to produce specific solution for example, production of HCL hydrochloric acid then solvent is specified by nature of the product, but if the principal purpose is to separate a particular component to remove certain component from mixture. For example, separation of H2S from natural gas, then choice of solvent is based on some important characteristics. Choice of solvent is based on some important properties. The first property is the solubility. As we said the good solvent in which solute is highly soluble. For example, if you take H2S and caustic soda then H2S is highly solvable in that solvent, but if the purpose of the solvent is to reuse again and recover the absorbed component, then the solvent should be chosen in such a way that the reactions with the solute should be reversible in nature.

So, instead of as the reactions of H2S with caustic soda is irreversible in nature. So, it is difficult to recover H2S from the solvent and reuse for further processing. So, instead of these the amines or methanol amine or ethanol amine are used for in which the reaction is reversible in nature. So, we can recover H2S and reuse amine. Another characteristic for the solvent or properties of the solvent should be volatility. The good solvent should be less volatile in nature, so that the solvent loss during the operations should be less, less volatile means the vapor pressure of the solvent should be less, less vapor pressure or low volatility.

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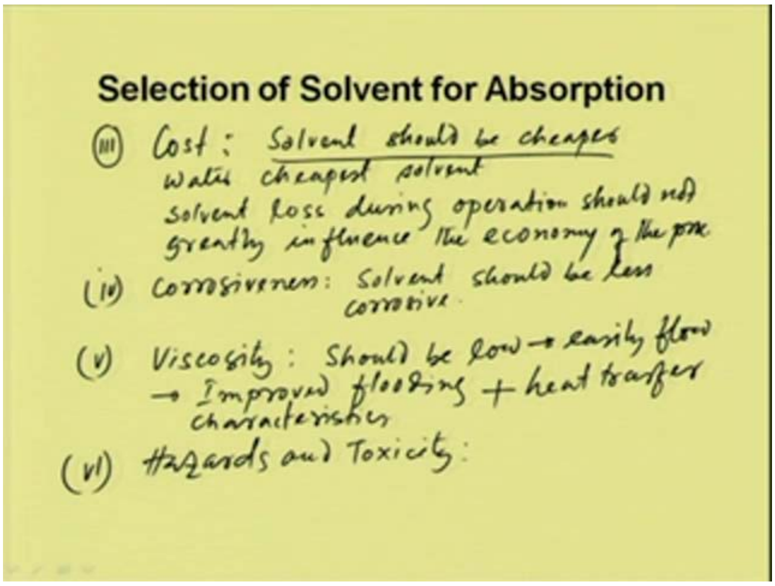

Selection of Solvent for Absorption

(iii) Cost : Solvent should be cheaper
water cheapest solvent
solvent loss during operation should not greatly influence the economy of the proc
(iv) Corrosiveness: Solvent should be less corrosive
(v) Viscosity : Should be low → easily flow
→ Improved flooding + heat transfer characteristics
(vi) Hazards and Toxicity :

Other important property is the cost. The solvent should be cheaper for example, water is the cheapest solvent, but depending on the application the solvent other properties has to be also considered. So, one we should see the solvent should be cheaper so that during the operations even if there is solvent loss, so which will not greatly influence the economy of the process. Solvent loss during operations should not greatly influence the economy of the process. Other important parameter is the corrosiveness. The solvent should be less corrosive so that we should not use expensive material for the contraction of the absorber, other important parameter is viscosity. So, the viscosity should be low so that it can easily flow and it improves the flooding and also heat transfer characteristics and another important point is hazard and toxicity.

The solvent should not be toxic and hazardous in nature and it should be non inflammable in nature. So, while selecting a particular solvent we need to consider these properties when the purpose of separation is to remove certain component from the gas mixture.

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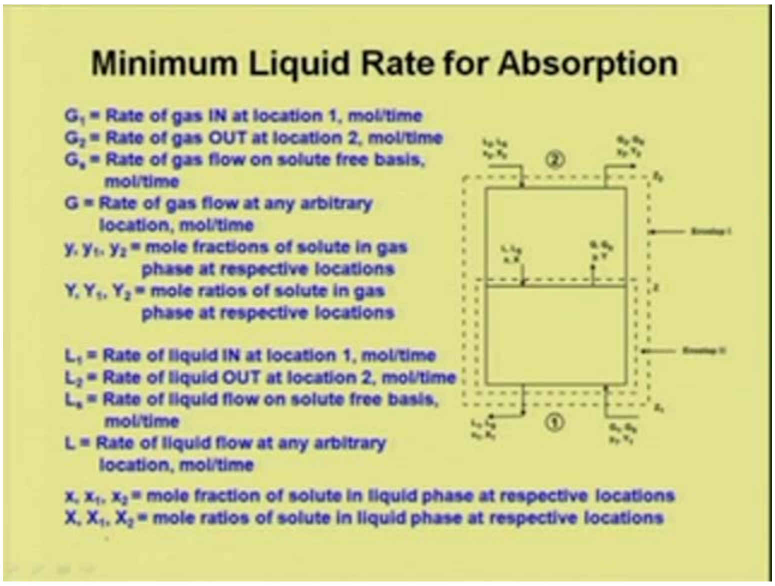

Minimum Liquid Rate for Absorption

G_1 = Rate of gas IN at location 1, mol/time
G_2 = Rate of gas OUT at location 2, mol/time
G_s = Rate of gas flow on solute free basis, mol/time
G = Rate of gas flow at any arbitrary location, mol/time
y, y_1, y_2 = mole fractions of solute in gas phase at respective locations
Y, Y_1, Y_2 = mole ratios of solute in gas phase at respective locations

L_1 = Rate of liquid IN at location 1, mol/time
L_2 = Rate of liquid OUT at location 2, mol/time
L_s = Rate of liquid flow on solute free basis, mol/time
L = Rate of liquid flow at any arbitrary location, mol/time
x, x_1, x_2 = mole fraction of solute in liquid phase at respective locations
X, X_1, X_2 = mole ratios of solute in liquid phase at respective locations

Now, for gas absorption operations as we can see for a particular absorber as shown in this figure, what is the liquid rate or minimum liquid rate we need to use for absorption operations? Let us consider as we have discussed earlier during module 2 stage wise operations module 2 and module 3 we have discussed this is the module absorber, if we consider like this where gas entered at the bottom of the column and exit at the a top of the column, liquid enters at the top of the column and exit at the bottom of the column. So, G 1, G 2 and G s and G these are gas flow rate and Gs is basically rate of gas flow on solute free free basis. And y small y, y 1 and y 2 these are the mole fractions of the solute in the gas phase at respective locations. Capital Y are the mole ratio of solute at gas phase at respective locations L 1 L 2 L s and L these are the liquid rates in and out at different locations. Small x is the mole fractions of the solute in the liquid phase and capital X is the mole ratio.

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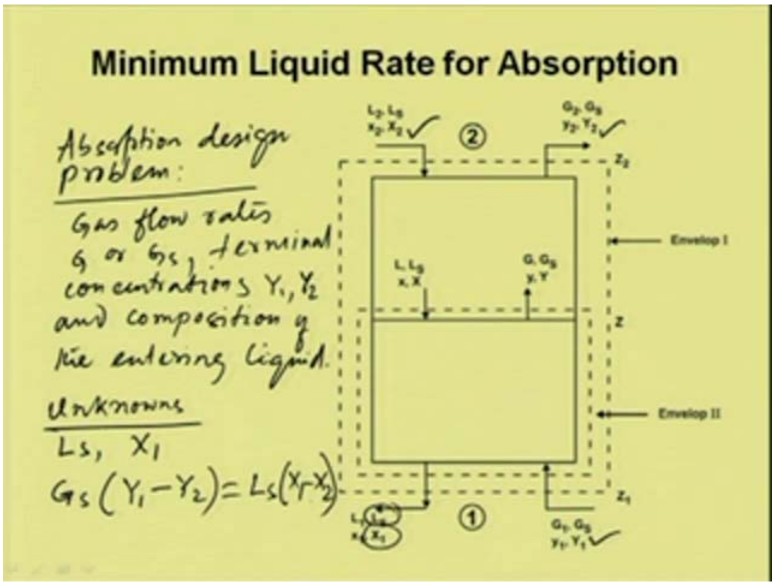

Minimum Liquid Rate for Absorption

Absorption design problem:

Gas flow rates G or Gs, terminal concentrations Y_1, Y_2 and composition of the entering liquid.

Unknowns

L_s, X_1

$G_s(Y_1 - Y_2) = L_s(X_1 - X_2)$

Now, for particular absorption design problem, what are the things, which is generally mentioned. One is the gas flow rates G or G s these are mentioned and the terminal concentrations of the gaseous components, terminal concentrations like y 2 and Y 1, these are mentions, Y 1, Y 2 and the composition of the entering liquid, composition of the entering liquid. So, this X 2 this is mentions. So, now our principal purpose is to get L s and X 1. So, these are unknowns. So, this unknowns are L s and X 1. So, this can be obtained if we consider envelop one the which is the whole conductor or absorber, then we can do the overall material balance and the overall material balance we can write G s into Y 1 minus Y 2 is equal to L s into X 1 minus X 2.

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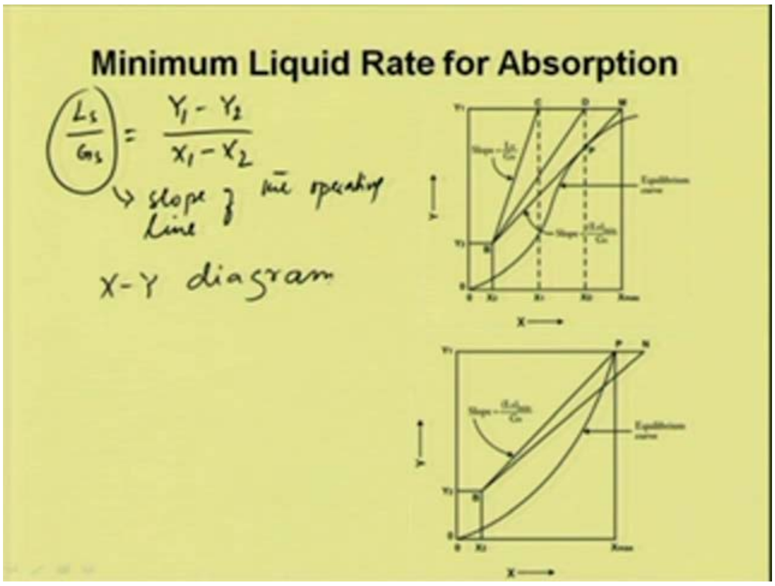

Minimum Liquid Rate for Absorption

$$\boxed{\frac{L_s}{G_s}} = \frac{Y_1 - Y_2}{X_1 - X_2}$$

↳ slope of the operating line

X-Y diagram

From these equations, we can write L s by G s is equal to Y 1 minus Y 2 divided by X 1 minus X 2. So, this is the slope of the operating line. Now, we know the terminal points Y 2 X 2 and we know the slope of the operating line and we can plot these operating line curve and which will cut the point Y 2 Y 1 line so that we can obtain X 1. So, this is the X Y diagram. So, there are two types of diagrams can be seen in which this is the equilibrium line and this is another equilibrium line.

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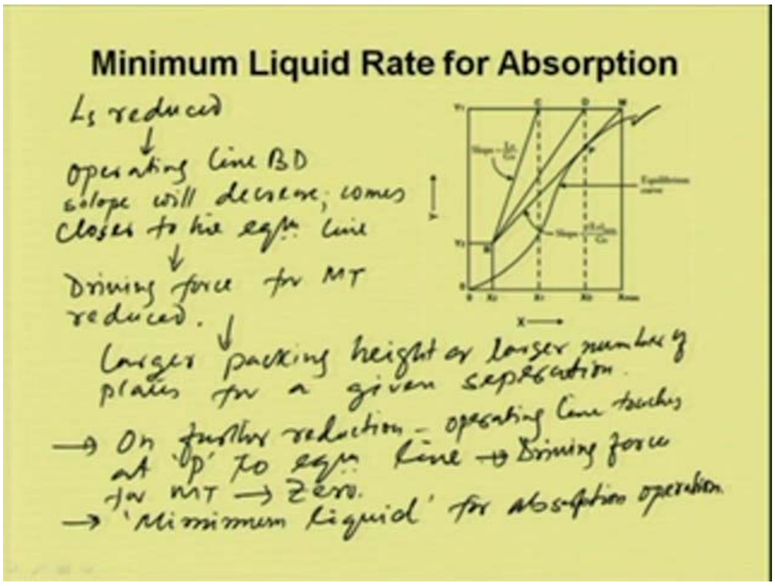

Minimum Liquid Rate for Absorption

L_s reduced
↓
operating line BD
slope will decrease, comes closer to the eqm. line
↓
Driving force for MT reduced.
↓
Larger packing height or larger number of plates for a given separation.

→ On further reduction – operating line touches at 'P' to eqm. line → Driving force for MT → zero.

→ 'Minimum liquid' for absorption operation

So, if we reduce the liquid flow rate L s, what happens the operating line BD, so this is B and D, this if we reduce the liquid flow rate the operating line slope will decrease. BD slope will decrease and this comes closer, closer to the equilibrium line. So, it this is the equilibrium line and so the operating line if we reduce the liquid rate operating line comes closer to the equilibrium line. So, in this case operating line comes closer to the equilibrium line means the driving force for mass transfer reduced. So, what we need, if driving force reduced we need larger packing height or large number of, larger number of plates for a given separation, but how long we can reduce the liquid flow rate.

So, we cannot reduce the liquid flow rate indefinitely. So, on further reductions as we can see at the fixed Y 2 and X 2 locations the slope of the operating line is further reduced where it touches to the equilibrium line. So, on further reduction it touches to the operating line touches at point P to the equilibrium line. So, at this point the driving force for mass transfer is 0. So, this is, this operating line the liquid rate corresponding to this operating line is known as the minimum liquid rate for absorption operation. This is theoretically possible.

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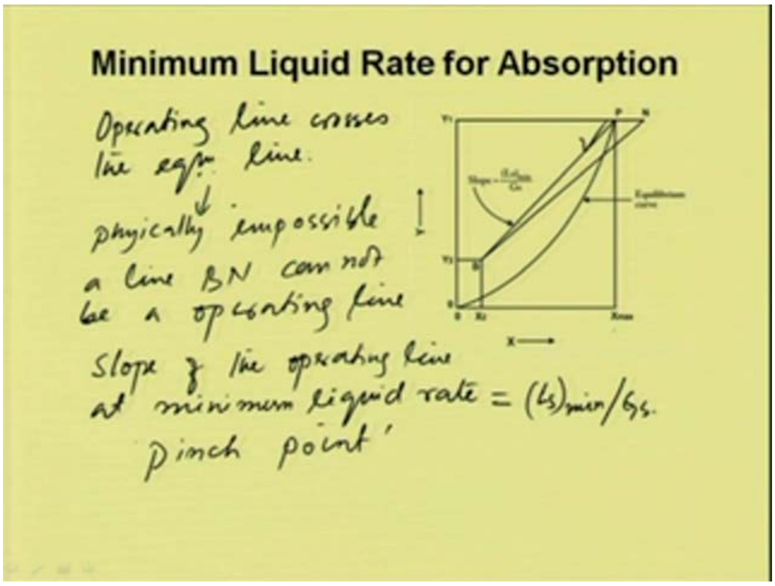

Minimum Liquid Rate for Absorption

Operating line crosses the eqm. line.
↓
physically impossible !
a line BN cannot be a operating line
Slope of the operating line at minimum liquid rate = $(L_s)_{min}/G_s$.
'pinch point'

Now, in another figure we can see if we further reduce the liquid rate the operating line crosses the equilibrium line, that means in one section of the column absorption is taking place and in other section of the column desorption occurs, which is physically impossible. So, a line like BN cannot be a operating line. So, the operating line equation so eventually this will not be the theoretically minimum liquid rate, even if it touches the equilibrium line and crosses the equilibrium line. So, this is not physically possible. So, the slope of operating line at minimum liquid rate would be equal to L s min by G s which is shown in this line. So, which is not crossed the equilibrium line, but touches the equilibrium line at some point.

Now, the exit concentration corresponding to this point is X max, this is the maximum possible concentrations of the solute in the liquid phase and as we said the driving force at this point is 0, mass transfer driving force at point P is 0 and this point is known as the pinch point. If it touches the equilibrium line then how many number of plates or tray we required for a given separations.

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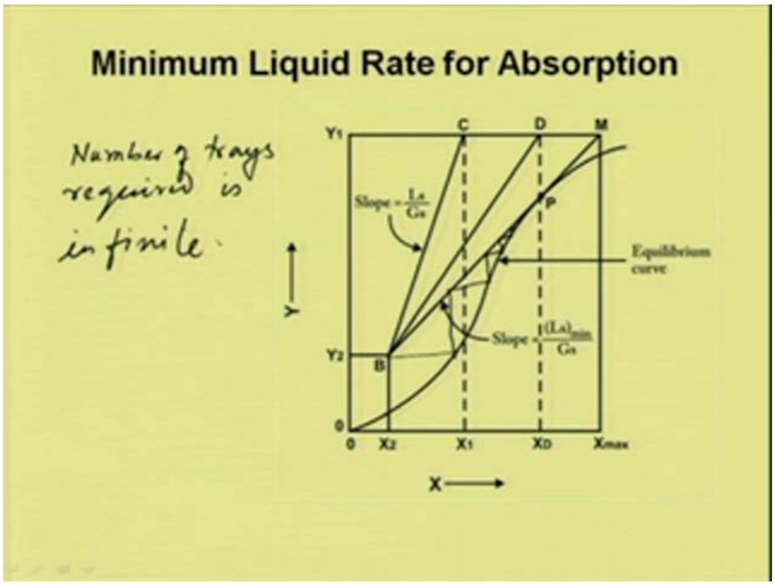

Minimum Liquid Rate for Absorption

Number of trays required is infinite.

So, if we chart at particular point and if we construct the line graphically if we do it, we can see as we reach to their pinch point the number of tray requires is infinite. So, at this point at minimum liquid rate where it touches the equilibrium line, the number of trays required is infinite. So, theoretically it is not possible to operate an absorber at infinite number of trays, so we cannot operate the absorber at minimum liquid rate. Now, we will give some closer view of minimum liquid rate for absorptions.

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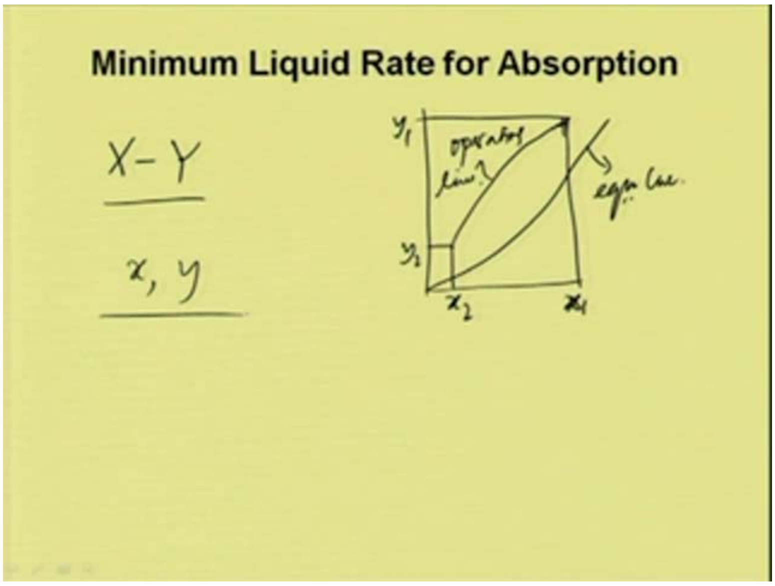

Minimum Liquid Rate for Absorption

X-Y

x, y

Now, if we plot the absorption curve instead of mole ratio, if we plot it mole fraction. So, this is exit concentration X 1 and this is X 2, this is Y 2, this is Y 1 and this is the equilibrium line and this the operating line. So, if we work on mole fractions then both the operating line and the equilibrium line are curved in nature. So, to obtain a pinch point in this case is difficult and we have to work with two different curves instead of state operating lines. So, for convenience we generally use the mole ratio units X Y plot instead of mole fractions plot x y curve.

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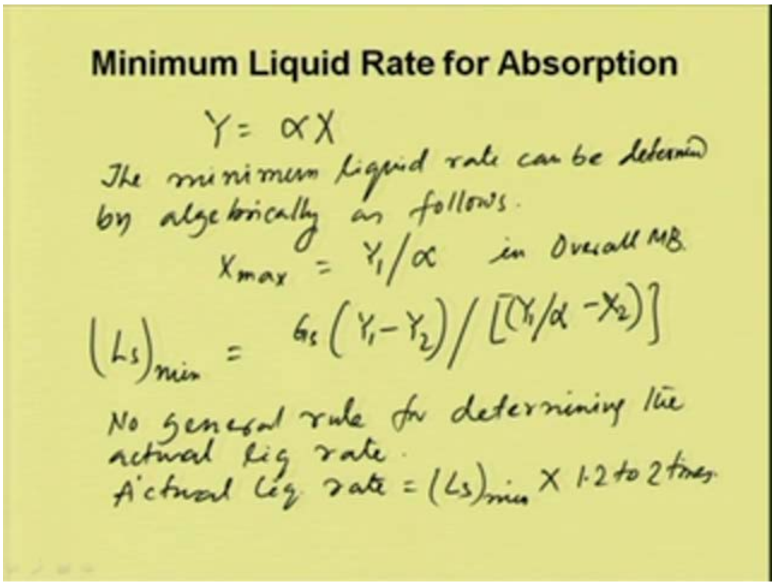

Minimum Liquid Rate for Absorption

$$Y = \alpha X$$

The minimum liquid rate can be determined by algebrically as follows.

$$X_{max} = Y_1/\alpha \quad \text{in Overall MB.}$$

$$(L_s)_{min} = G_s(Y_1 - Y_2)/[(Y_1/\alpha - X_2)]$$

No general rule for determining the actual liq rate.

Actual liq rate = $(L_s)_{min} \times 1.2$ to 2 times.

Now, if the equilibrium relationship as we said it is generally curved line, but if the relation is represented in linear in nature like Y is equal to alpha X, the minimum liquid rate can be determined by algebraically as follows. X max should be Y 1 by alpha and if we substitute this in the overall material balance equation then L s minimum would be G s into Y 1 minus Y 2 divided by capital Y 1 by alpha minus X 2. Now, as we said the absorber cannot operate at minimum liquid rate, so and there is no general rule for determining the actual liquid rate. In general the actual liquid rate is equal to L s minimum into 1.2 to 2 times.

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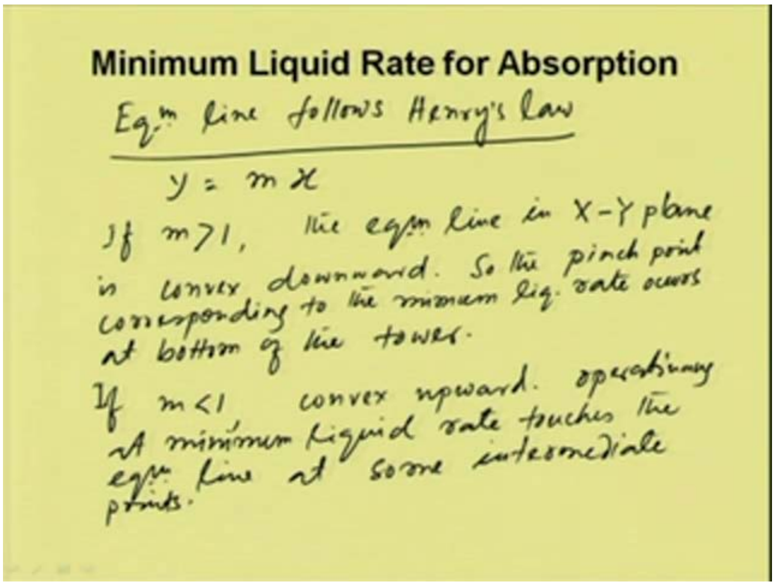

Minimum Liquid Rate for Absorption

Eq^{m} line follows Henry's law

$y = m x$

If $m > 1$, the eq^{m} line in X-Y plane is convex downward. So the pinch point corresponding to the minimum liq. rate occurs at bottom of the tower.

If $m < 1$ convex upward. operating line at minimum liquid rate touches the eq^{m} line at some intermediate points.

In this connection we will discuss more detail of the nature of the curve and the equilibrium relationship. Suppose, if the equilibrium line follows Henry’s law in that case y is equal to m x and if m greater than 1, the equilibrium line in X Y plane is convex downward. So, the pinch point, point corresponding to the minimum liquid rate occurs at bottom of the tower and if m less than 1 then equilibrium curve is convex upward, so the operating line at minimum liquid rate touches at some intermediate points touches the equilibrium line at some intermediate points.

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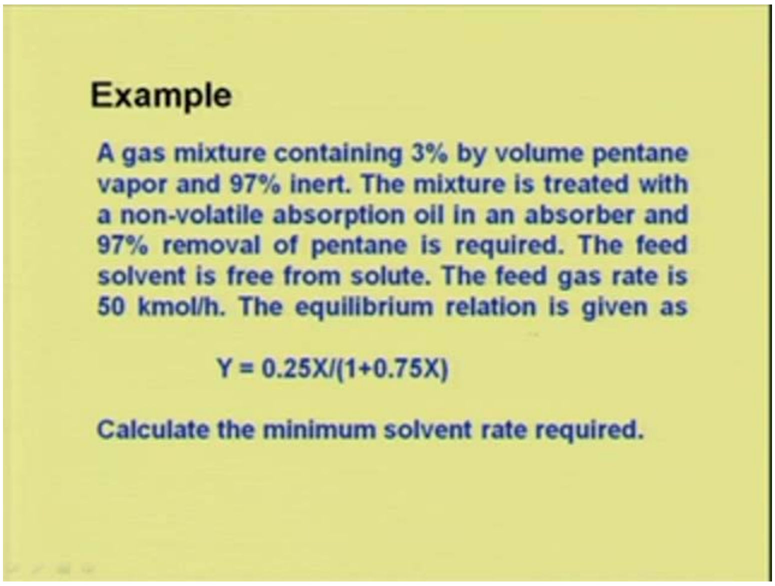

Example

A gas mixture containing 3% by volume pentane vapor and 97% inert. The mixture is treated with a non-volatile absorption oil in an absorber and 97% removal of pentane is required. The feed solvent is free from solute. The feed gas rate is 50 kmol/h. The equilibrium relation is given as

$$Y = 0.25X/(1+0.75X)$$

Calculate the minimum solvent rate required.

Now, let us take very simple example, if we take a gas mixture containing 3 percent by volume pentane vapor and 97 percent inert, the mixture is treated with a non-volatile absorption oil in an absorber and 97 percent removal of pentane is required. The feed solvent is free from solute, the feed gas the rate is 50 k mole per hour. The equilibrium relations is given, calculate the minimum solvent rate required.

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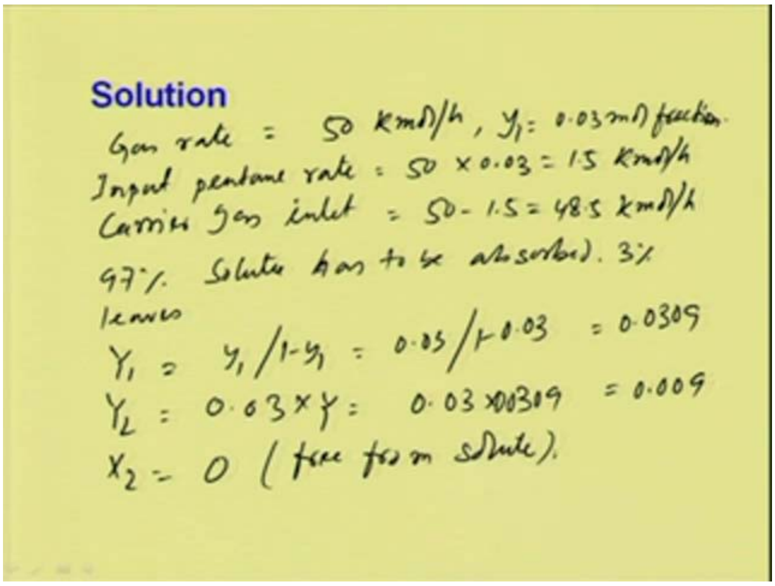

Solution

Gas rate = 50 kmol/h, y_1 = 0.03 mol fraction

Input pentane rate = $50 \times 0.03 = 1.5$ kmol/h

Carrier gas inlet = $50 - 1.5 = 48.5$ kmol/h

97% solute has to be absorbed. 3% leaves

$Y_1 = y_1/1-y_1 = 0.03/1-0.03 = 0.0309$

$Y_2 = 0.03 \times Y = 0.03 \times 0.0309 = 0.009$

$X_2 = 0$ (free from solute).

So, the given gas rate is 50 k mole per hour and y 1 0.03 mole fraction input rate of pentane. So 1.5 k mole per hour carrier gas, gas inlet is 50 minus 1.5 is equal to 48.5 k mole per hour. Now, 97 percent solute has to be absorbed, to be absorbed. Therefore, 3 percent leaves with the carrier, leaves, so capital Y 1 is y 1 by 1 minus y 1, so which is 0.03 divided by 1 minus 0.03 which is 0.0309 and Y 2 is 0.03 into y 1 which is 0.03 into 309 which is equal to 0.009 and also X 2 is 0 free from solute.

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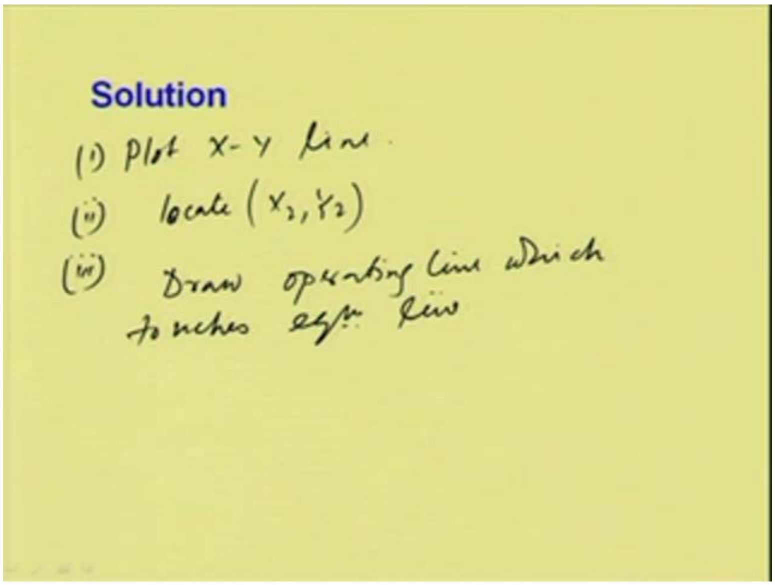

Solution

(i) Plot x-y line.

(ii) locate (X_2, Y_2)

(iii) Draw operating line which touches eqm. line

Now, what are the steps we follow, we plot the equilibrium line and then we locate x 2, y 2 and then we draw operating line. Line which touches equilibrium line and then point of tangency correspond to the minimum liquid rate.

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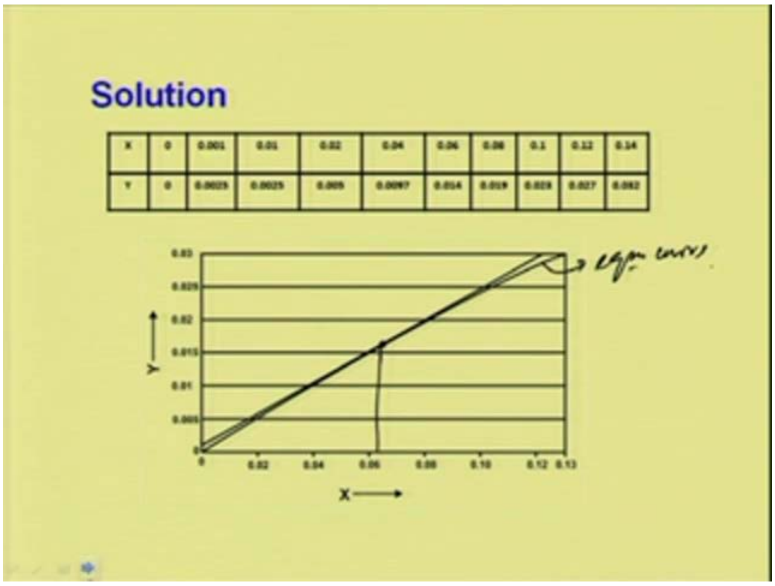

Solution

X	0	0.001	0.01	0.02	0.04	0.06	0.08	0.1	0.12	0.14
Y	0	0.0025	0.0025	0.005	0.0097	0.014	0.019	0.023	0.027	0.032

Then if we take the x y as the equation is given. So, this is the equilibrium data and this is the equilibrium curve and we know the point at the bottom of the tower and then we plot with the slope and it touches at this point.

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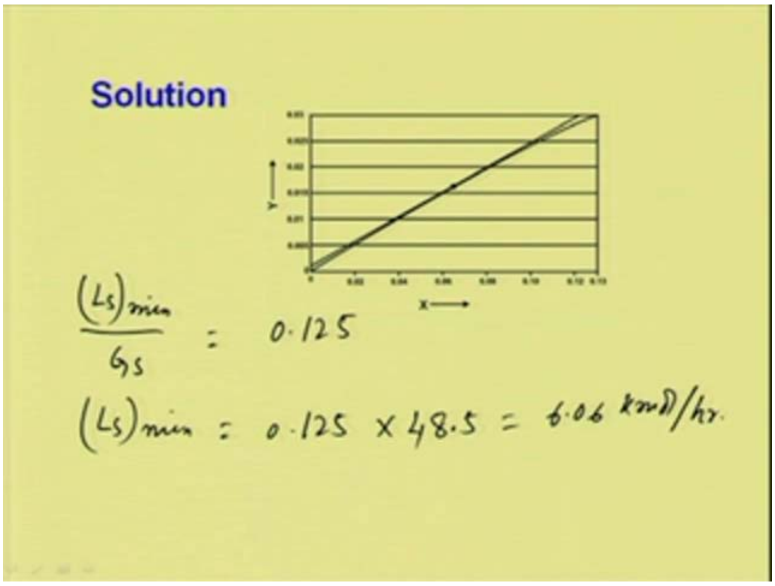

Solution

$$\frac{(L_s)_{min}}{G_s} = 0.125$$

$$(L_s)_{min} = 0.125 \times 48.5 = 6.06 \text{ kmol/hr.}$$

So, from this we can calculate L s min by G s, which is around 0.125 from the figure. So, L s minimum will be 0.125 multiplied by 48.5, so which is about 6.06 k mole per hour.

Thank you.