Mass Transfer Operations I

Prof. Bishnupada Mandal
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Module - 2
Mass Transfer Coefficients
Lecture - 6
Inter phase Mass Transfer and Mass Transfer Theories Part 1

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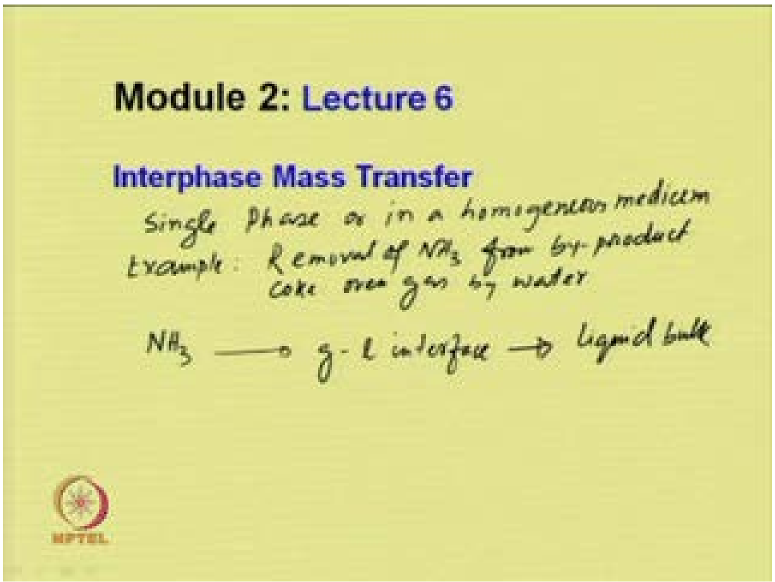

Module 2: Lecture 6

Interphase Mass Transfer

Single Phase or in a homogeneous medium

Example: Removal of NH_3 from by-product coke oven gas by water

$NH_3 \longrightarrow$ g-l interface $\rightarrow$ liquid bulk

Welcome to sixth lecture of module two, which is on mass transfer coefficients. In this lecture we will discuss the inter phase mass transfer. In the previous lecture, we have considered mass transfer theories, particularly the mass transfer coefficient in turbulent flow. And we have discussed the two important theories; the penetration theory, and the surface renewal theory, and how to derive the correlations or the equation for these theories to calculate the mass transfer coefficients. So far, we have discussed diffusion mass transfer in single phase or in a homogeneous medium. But most of the mass transfer operation in practice, involved transport of one component to the other component between the phases, between two phases, and the phases are insoluble in nature.

Suppose, if we consider the removal of ammonia, from by product coke oven gas by water, absorption in water. So, in this case ammonia diffuses from the gas bulk phase to the gas liquid interface, and then from gas liquid interface it is transported to the liquid bulk, and this is one of the example of inter phase mass transfer. There are many other similar examples are available for gas liquid interface mass transfer. Like, if we consider the removal of objects enable for H 2 s or sulphur dioxide gas is by alkaline solution; that is also a two phase system, gas and liquid system, and it is another example of inter phase mass transfer. Then how can we calculate the rate of mass transfer in two phase system.

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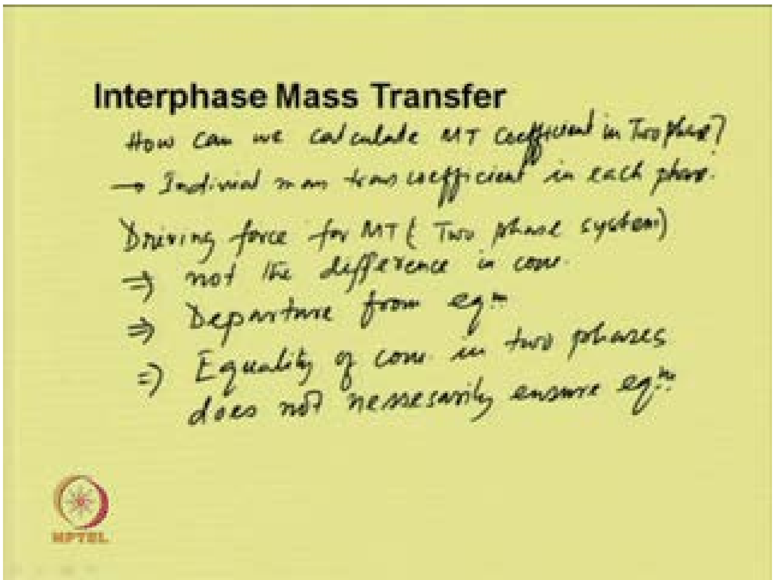

Interphase Mass Transfer

How can we calculate MT coefficient in Two phase?

→ Individual mass trans coefficient in each phase.

Driving force for MT (Two phase system)

⇒ not the difference in conc.

⇒ Departure from eqm

⇒ Equality of conc in two phases does not nessesarily ensure eqm.

So, in two phase system, how can we calculate mass transfer coefficient. Since the diffusion and mass transfer takes place in both the phases, gas phase and the liquid phase. So, we have to take into account, the individual mass transfer coefficient separately. As we discussed in our module one, the driving force for mass transfer, sorry mass transfer in two phase system, not the concentration gradient, not the difference in concentration. The driving force is basically the departure from equilibrium, and equality of concentration in the two phases, does not ensure equilibrium. Then what is the true driving force for mass transfer, in case of equilibrium between the phases.

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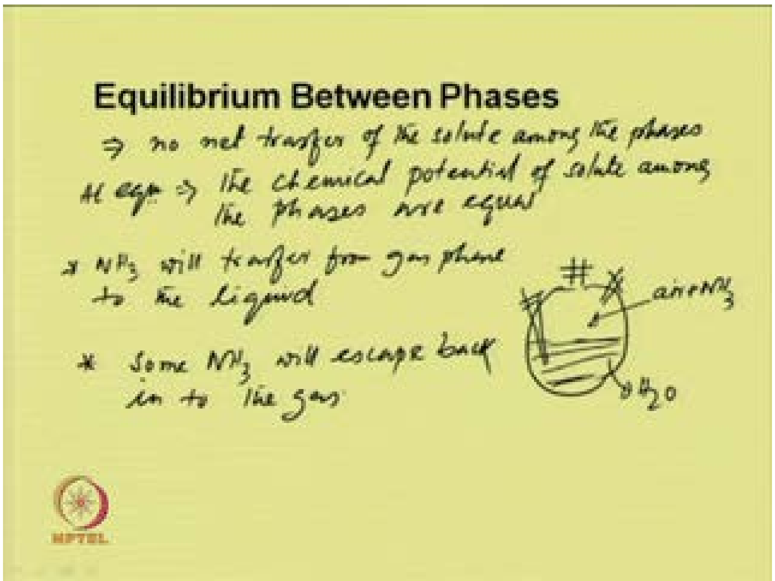

Equilibrium Between Phases

⇒ no net transfer of the solute among the phases

At eqm ⇒ the chemical potential of solute among the phases are equal

* NH_3 will transfer from gas phase to the liquid

* Some NH_3 will escape back in to the gas

When we say equilibrium between two phases, we say that, no net movement or no net transfer of the solute, among the phases. At equilibrium, the chemical potential of the solute, among the phases are equal. So, the equality of the chemical potential, will tell the equilibrium states, and that time there will be no net transfer of the solute among the phases. Now, let us consider a simple example, how to calculate the equilibrium concentration. So consider a simple tank, which is partially filled with water, and in which some amount of air and ammonia mixer is introduced, the vessel is closed. So, as soon as the air ammonia mixer comes in contact, ammonia will transfer, since it is soluble in water, from gas phase to the liquid, and simultaneously, some ammonia will escape back into the gas.

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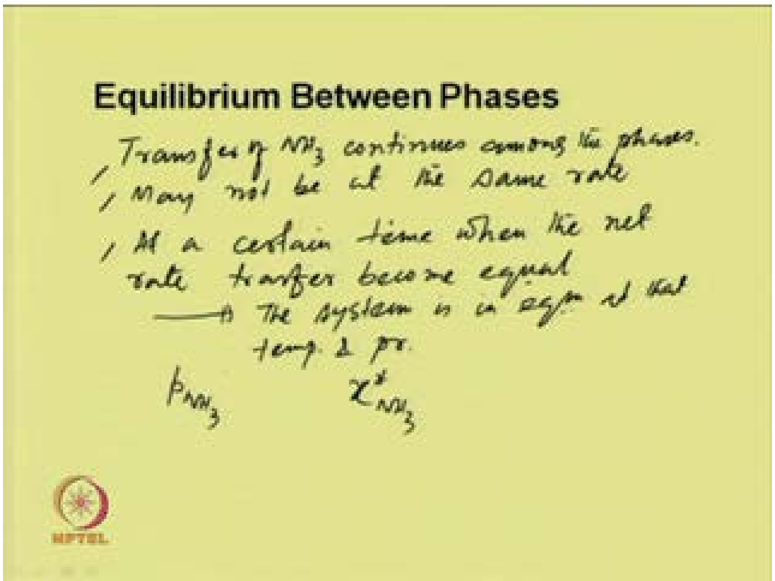

Equilibrium Between Phases

- Transfer of NH_3 continues among the phases.
- May not be at the same rate
- At a certain time when the net rate transfer become equal

$\longrightarrow$ The system is in eqm at that temp. & pr.

p_{NH_3} $x^*_{NH_3}$

And this process of transfer from the gas to the liquid will continues, among the phases, and they may not be at the same rate. So, at a time, when the net rate of transfer become equal, then we says that the process is in equilibrium, system is in equilibrium at that temperature and pressure. So, if we take a small sample from this, so liquid sample we can collect from here, and gas sample we can collect from here, and we can analyze their concentration, both in the gas phase and the liquid phase. So, we will get the partial pressure of ammonia, in the gas phase, and the corresponding mole fractions in the liquid phase is x N x 3 star. So, this is the liquid phase concentration, equilibrium concentration, and it is the equilibrium partial pressure, at this temperature and pressure. Now, if we inject some more ammonia into the system, then keeping temperature and pressure constant, then it will each another equilibrium concentration.

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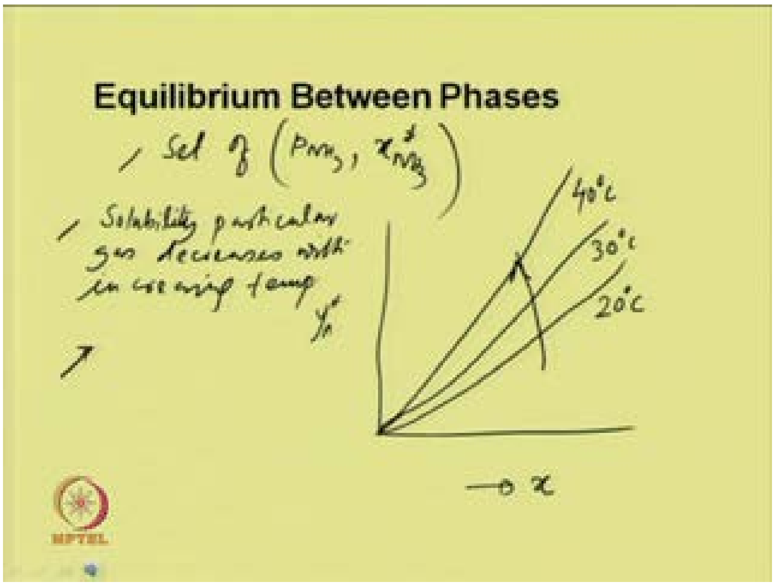

Equilibrium Between Phases

- set of $(p_{NH_3}, x^*_{NH_3})$
- Solubility particular gas decreases with increasing temp

Again, we will obtain a set of p N H 3 and x N H 3 star, and if we plot them, it is known as the equilibrium curve at that temperature and pressure; say it is at 20 degree centigrade. Similarly, if we change the temperature, and do the similar experiments, will obtain another set of equilibrium data; say it is at 30 degree centigrade, and say it is at 40 degree centigrade. So, this is the y A star, and this is liquid phase or in terms of partial pressure and the liquid phase mole fractions we can define it. So, this is the equilibrium curve, typically equilibrium curve. We can see that the solubility of ammonia, solubility of particular gas, decreases with increasing temperature, and the equilibrium curve becomes more steeper. Now, how to calculate number of independent state properties required to define the system.

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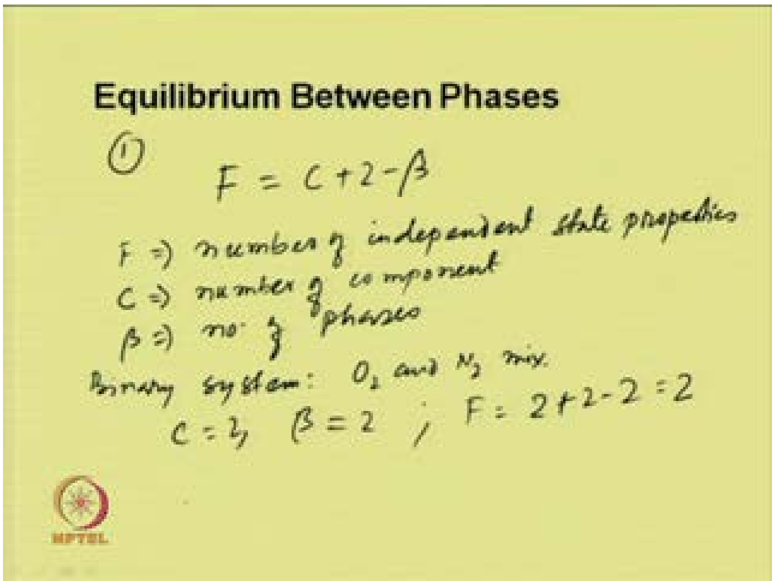

Equilibrium Between Phases

①

$$F = C + 2 - \beta$$

$F \Rightarrow$ number of independent state properties

$C \Rightarrow$ number of component

$\beta \Rightarrow$ no. of phases

Binary system: O_2 and N_2 mix.

$C = 2, \ \beta = 2 \ ; \ F = 2 + 2 - 2 = 2$

So, we can define the state of the system, by gibs phase rule, which states that F is equal to C plus 2 minus beta. F is the number of independent state properties, to define a system state properties, C is the number of component, and beta is the number of phases. Now, if we consider a binary system, oxygen and nitrogen mixture gas liquid system. So, in this case, the component is 2, number of phases is beta is also 2, so F is equal to C plus; that is 2 plus 2 minus 2 is equal to 2. So, the independent properties required to specify the system is 2. So, if we generally take the temperature pressure and composition of the system, as the independent variables state properties, then if we mention temperature and pressure, the composition is automatically fixed.

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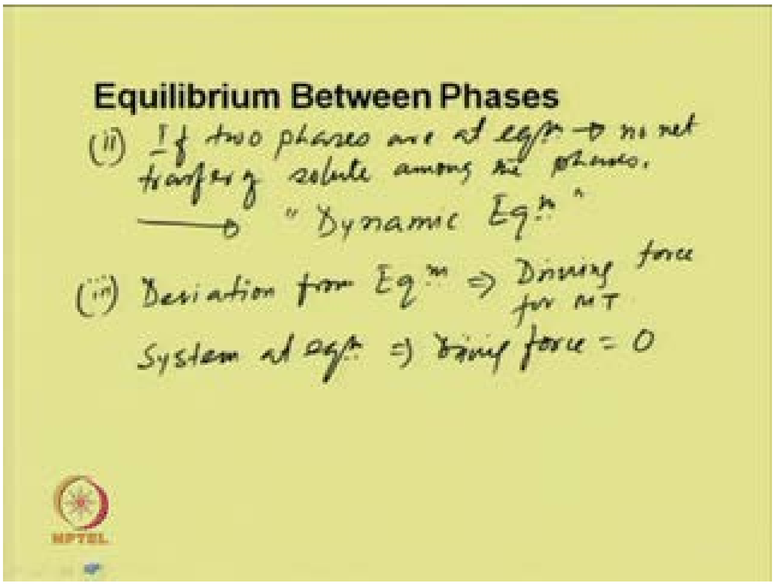

Equilibrium Between Phases

(ii) If two phases are at eq^{m} → no net transfer of solute among the phases.
→ "Dynamic Eq^{m}"

(iii) Deviation from Eq^{m} ⇒ Driving force for MT

System at eq^{m} ⇒ Driving force = 0

Another important thing from the equilibrium curve can be drawn that, if two phases are at equilibrium, there is no net transfer of solute among the phases. This does not mean that there is no transfer of solute among the phases, but the solute move from one phase to the other phase are in same rate, and we say that the dynamic equilibrium is reached. And third thing is that, as we said earlier also the deviation from equilibrium is the driving force for mass transfer system at equilibrium, driving force is equal to 0.

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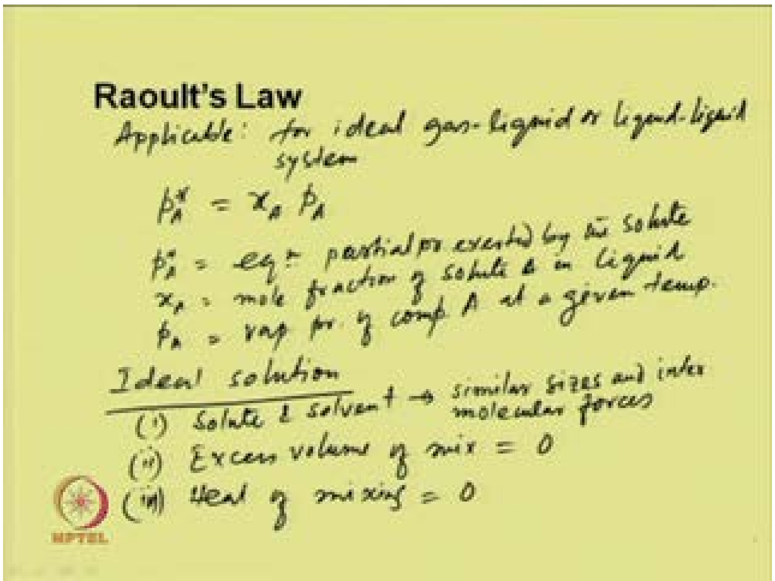

Raoult's Law

Applicable: for ideal gas-liquid or liquid-liquid system

$p_A^* = x_A P_A$

p_A^* = eq^{m} partial pr exerted by the solute

x_A = mole fraction of solute A in liquid

P_A = vap pr of comp A at a given temp.

Ideal solution

(i) Solute & solvent → similar sizes and inter molecular forces

(ii) Excess volume of mix = 0

(iii) Heat of mixing = 0

Now, to calculate the equilibrium data, we mainly depend on the experimental data. There are some attempts to calculate the equilibrium data theoretically. Two important laws of equilibrium relations between the phases are very important those are Raoult's law and the Henry's law. The Raoult's law is applicable for ideal gas liquid, or liquid system, and it is expressed as p A star is equal to x A into p A, where p A star is the equilibrium partial pressure, exerted by the solute, x A is the mole fractions of solute A in liquid, and p A is the vapor pressure of A, component A at a given temperature. The solutions which we say the ideal solutions, will have the following properties. The solute and the solvent, this would be similar size and intermolecular forces. Excess volume of mixing, is equal to 0, and heat of mixing is 0 for both solute and the solvent if they are in liquid phase.

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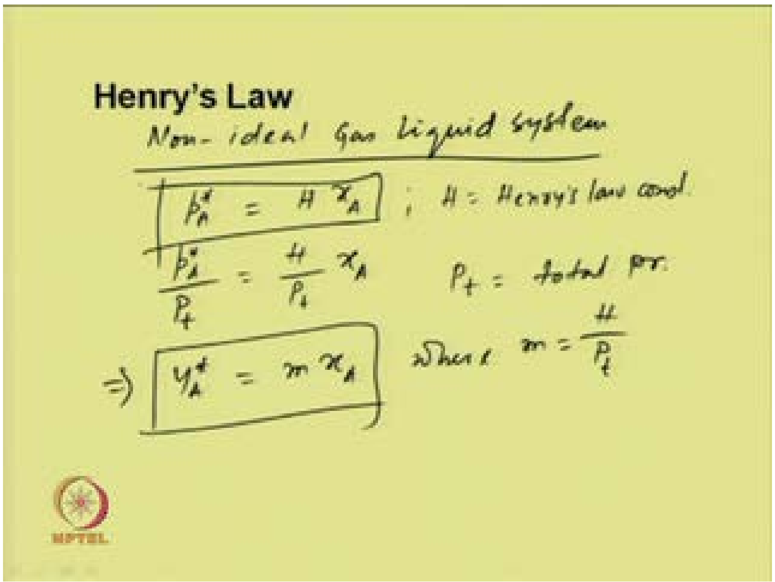

Henry's Law

Non-ideal Gas liquid system

$$\boxed{p_A^* = H x_A} \; ; \; H = \text{Henry's law const.}$$

$$\frac{p_A^*}{P_t} = \frac{H}{P_t} x_A \qquad P_t = \text{total pr.}$$

$$\Rightarrow \boxed{y_A^* = m x_A} \qquad \text{where } m = \frac{H}{P_t}$$

The Henry's law which states that and this is applicable for non-ideal gas liquid systems, and the important form of Henry's law is that partial pressure. Equilibrium partial pressure is equal to H x A, H is the Henry's law constant, p A star; the equilibrium partial pressure of A, and x A is the mole fractions of the liquid. And then if we divide these equations by p t p A star, by p t the total pressure is equal to H by p t x A. So, this is y A star is equal to m x A, where m is equal to H by p t, p t is the total pressure. So, this is another form of Henry's law

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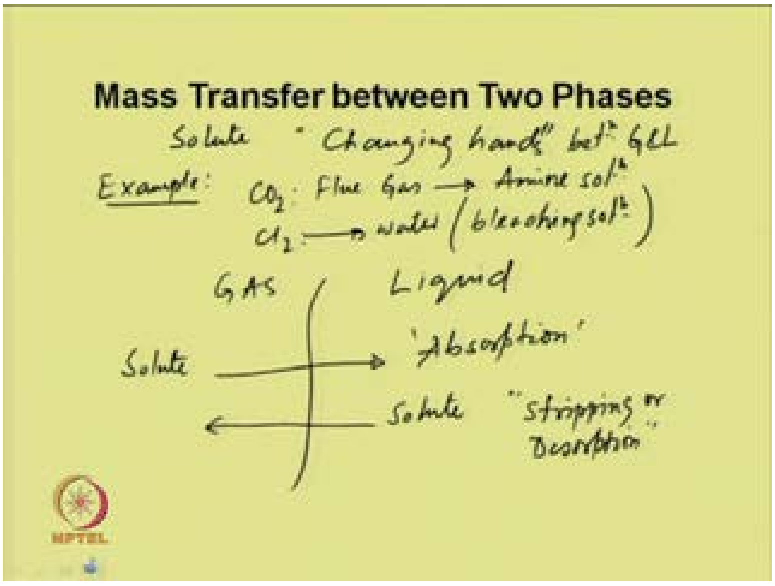

Mass Transfer between Two Phases

Solute "Changing hands" betn G&L

Example: CO_2: Flue Gas → Amine soln
Cl_2 → water (bleaching soln)

GAS | Liquid

Solute → 'Absorption'

← Solute "Stripping or Desorption"

Now, we will discuss the mass transfer between the phases, as we said the majority of the industrial applications, involved mass transfer between two phases, or sometimes three phases as well. And the phases they are immiscibly in nature, if we consider a solute changing, hence between gas and liquid. For example, removal of CO2 from flue gas, using amine solution chlorine forms with water, form bleaching solution. So, in this case, the absorption of a solute into the liquid or the desorption of a particular component from the liquid, when solute transfer from gas phase to the liquid phase, we called absorption, and when it transfer from solute, we call it stripping or desorption.

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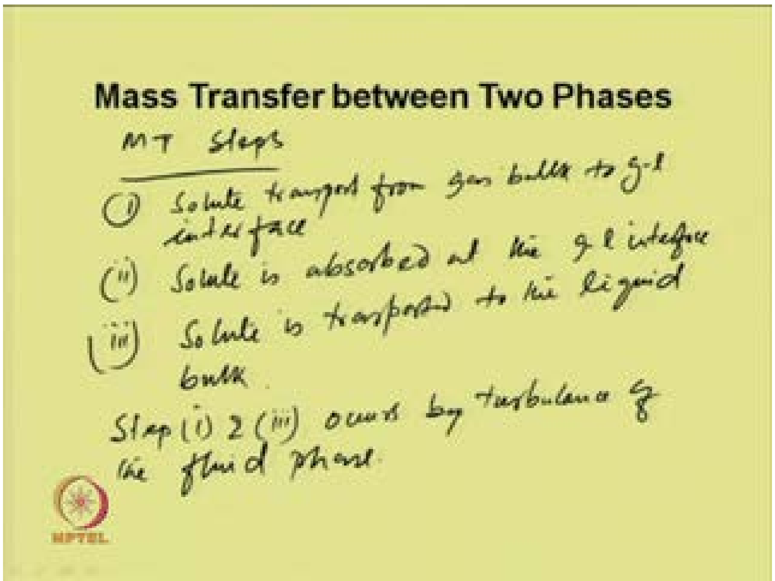

Mass Transfer between Two Phases

MT Steps

(i) Solute transport from gas bulk to g-l interface

(ii) Solute is absorbed at the g-l interface

(iii) Solute is transported to the liquid bulk.

Step (i) & (iii) occurs by turbulence of the fluid phase.

The concentration near the interface changes, and the mass transfer takes place in three steps; solute transport from gas bulk, to gas liquid interface, then at the interface, solute is absorbed at the gas liquid interface, and third solute is transported to the liquid bulk. The transfer of step one and three occurs by turbulence of the fluid phase.

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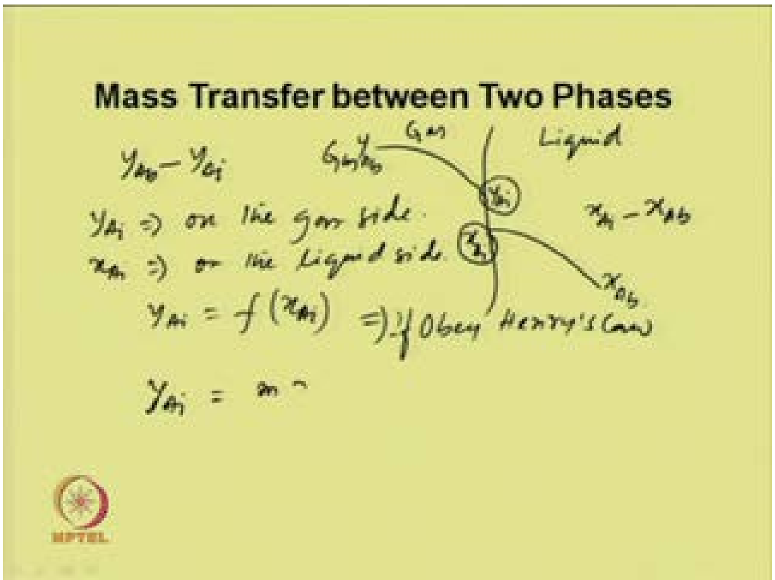

Mass Transfer between Two Phases

$y_{Ab} - y_{Ai}$

y_{Ai} ⇒ on the gas side.

x_{Ai} ⇒ on the Liquid side.

$y_{Ai} = f(x_{Ai})$ ⇒ if Obey Henry's Law

$y_{Ai} = m$

The transfer of solute from the gas, suppose y A bulk, and this is y A i at the interfacial concentration, this is x A i and x A b. So, the driving force in the gas phase is y A B minus y A i, and in the liquid phase is x A i minus x A B. So, what does it mean this y A i and x A i, these are the interfacial concentration. Physically it means that y A i is the interfacial concentration of A on the gas side, and x A i is on the liquid side. Generally at the interface mass transfer is assumed least at equilibrium. So, there will be equilibrium between y A i and x A i. So, we can write y A i is a function of x A i. If it obeys Henry's law, then we can write y A i is equal to M x A i.

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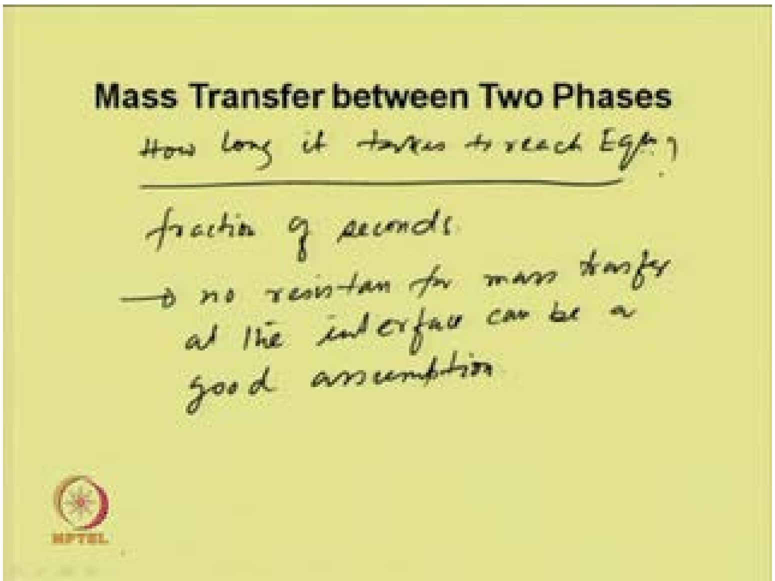

Mass Transfer between Two Phases

How long it takes to reach Eqm?

fraction of seconds

→ no resistan for mass trnsfr at the interface can be a good assumption

If the two phases are not in equilibrium, then how long it takes to reach equilibrium. To attain the equilibrium, it takes fraction of seconds. So, we called, there is no resistance at the interface for mass transfer at the interface, can be a good assumption.

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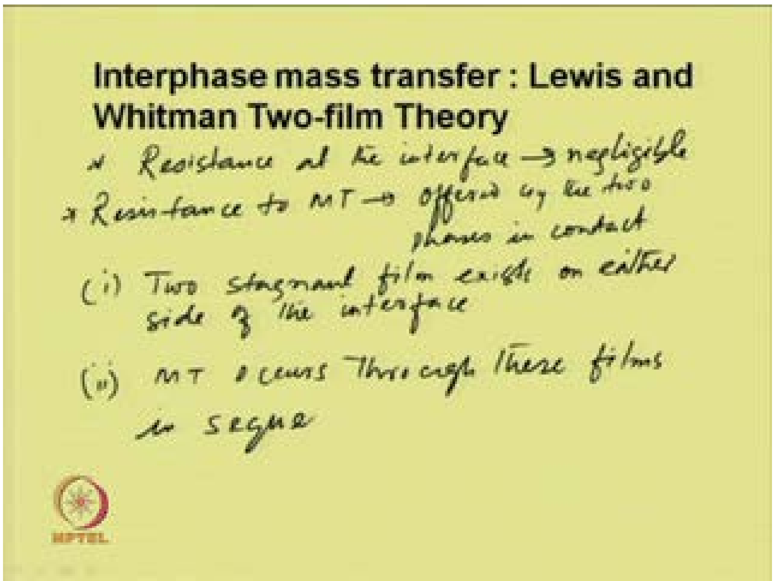

Interphase mass transfer : Lewis and Whitman Two-film Theory

- * Resistance at the interface → negligible
- * Resistance to MT → offered by the two phases in contact

(i) Two stagnant film exists on either side of the interface

(ii) MT occurs through these films in segue

However, there are some exceptions in this case as well. As we said resistance at the interface is negligible, and resistance to mass transfer, offered by the two phases in contact. This is how the Lewis and Whitman in 1924, they visualized the interface mass transfer among the phases. They said that two stagnant films exist on either side of the interface, and mass transfer occurs through these films in sequence.

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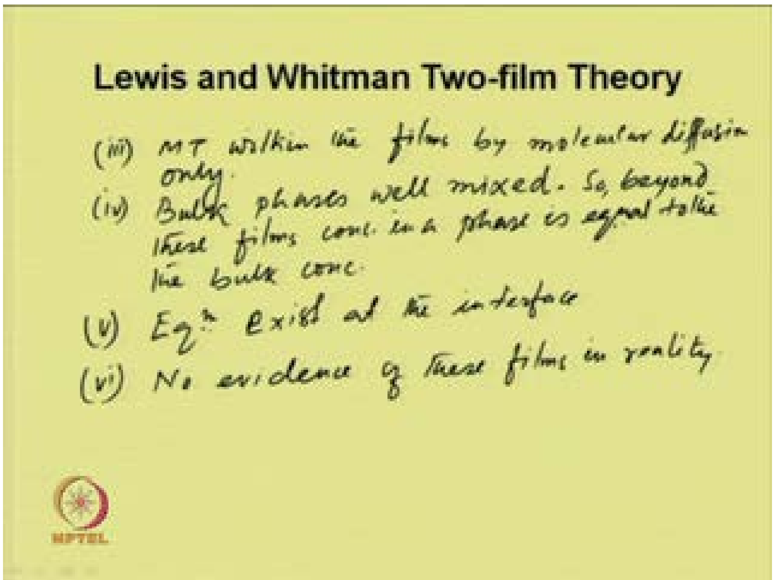

Lewis and Whitman Two-film Theory

(iii) MT within the films by molecular diffusion only.

(iv) Bulk phases well mixed. So, beyond these films conc. in a phase is equal to the the bulk conc.

(v) Eq^{n} exist at the interface

(vi) No evidence of these films in reality

Third one; they said mass transfer within the film by molecular diffusion only. Bulk phases well mixed, so beyond these films, concentration in a phase is equal to the bulk concentration. Equilibrium exists at the interface. No evidence of these films in reality.

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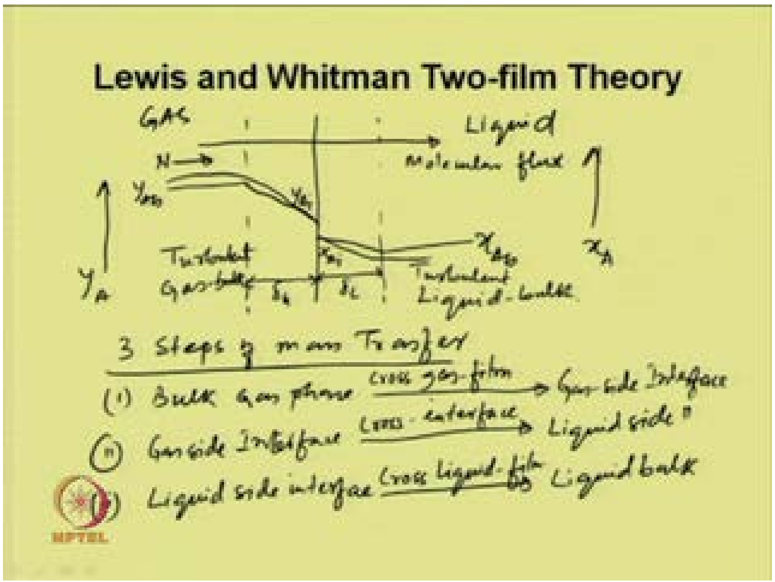

Lewis and Whitman Two-film Theory

3 Steps of mass Transfer

(i) Bulk gas phase $\xrightarrow{\text{Cross gas-film}}$ Gas side Interface

(ii) Gas side Interface $\xrightarrow{\text{Cross-interface}}$ Liquid side "

(iii) Liquid side interface $\xrightarrow{\text{Cross liquid-film}}$ Liquid bulk

So, according this Lewis and Whitman two film theory, we can see that there is a liquid side film, and this is gas side film. This is a delta g and this is a delta l, liquid film, and this is the molecular flux. Suppose, this is y A B bulk concentration x A B, this is the liquid bulk concentration, and this is x A i this is y A i. And we call, this is turbulent bulk, gas bulk, and this is turbulent liquid bulk. So, three steps of mass transfer; one is bulk gas phase to gas side interface, and it will cross gas film. Second, gas side interface to liquid side interface, it will cross interface. And third, liquid side interface to liquid bulk, so it will cross liquid film. So, the concentration gradient in the liquid film is linear, but the true concentration driving force is parabolic in nature.

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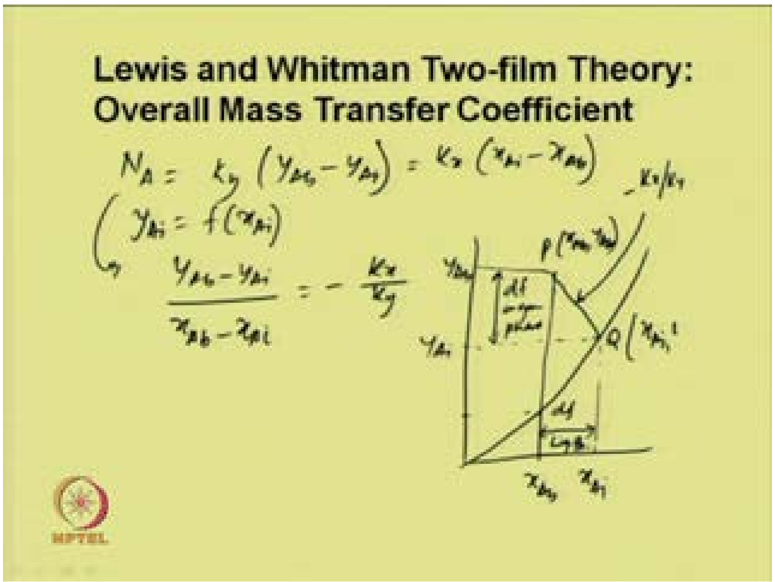

Lewis and Whitman Two-film Theory:
Overall Mass Transfer Coefficient

$$N_A = k_y\left(y_{Ab} - y_{Ai}\right) = k_x\left(x_{Ai} - x_{Ab}\right)$$

$$y_{Ai} = f(x_{Ai})$$

$$\frac{y_{Ab} - y_{Ai}}{x_{Ab} - x_{Ai}} = -\frac{k_x}{k_y}$$

The flux N A from the figure we can write k y, y A B minus y A i is equal to k x x A i minus x A B, and y A i function of x A i, so equilibrium exist. And from this we can obtain y A B minus y A i divided by x A B minus x A i is equal to minus k x by k y. So, if we plot, in terms of driving force, suppose this is your equilibrium curve, and this is the point p of x A B y A B, then this is x A B, y A B bulk concentration. And this is the slope of the curve, which is minus k x by k y. This will give you the x A i, and this will give you y A i. So, this is the driving force in gas phase, and this is the driving force in liquid phase, and suppose this is q which is x A i y A i.

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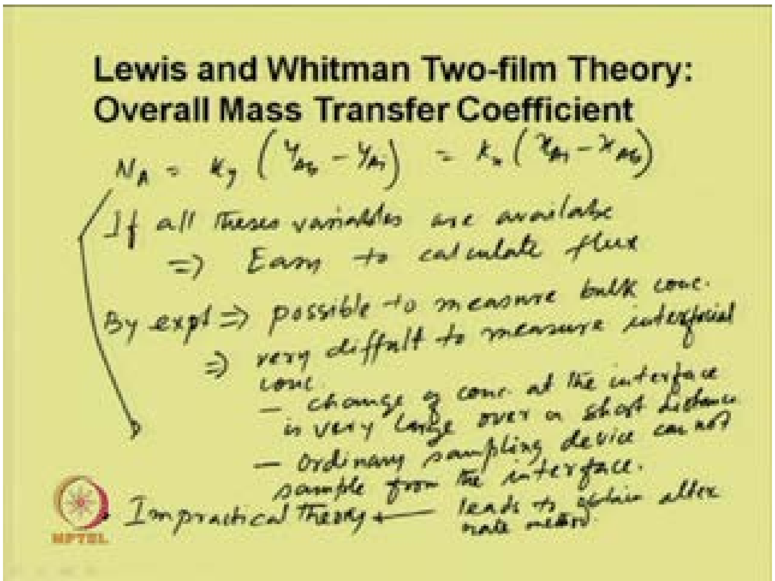

Lewis and Whitman Two-film Theory: Overall Mass Transfer Coefficient

$N_A = k_y (y_{AB} - y_{Ai}) = k_x (x_{Ai} - x_{AB})$

If all theses variables are availabe
⇒ Easy to calculate flux

By expt ⇒ possible to measure bulk conc.
⇒ very diffult to measure interfacial conc.
– change of conc. at the interface is very large over a short distance
– ordinary sampling device cannot sample from the interface.

Impractical Theory ← leads to obtain alternate method

Now, N A is equal to k y, y A B minus y A i is equal to k x x A i minus x A B. If all these variables are available, then it is easy to calculate flux. By experiment we can measure only the bulk concentrations, because the measurement of the interfacial concentration is very difficult. So, no devices are available to calculate the interfacial concentration. So, by experiment only it is possible to measure bulk concentration, and very difficult to measure interfacial concentration, because change of concentration at the interface is very large over a solved distance. So, ordinary sampling device cannot sample from the interface. So, the above relation N A is not useful for mass transfer calculations, this means impractical theory. Since the theory is impractical to calculate the flux, this leads to obtain alternate method.

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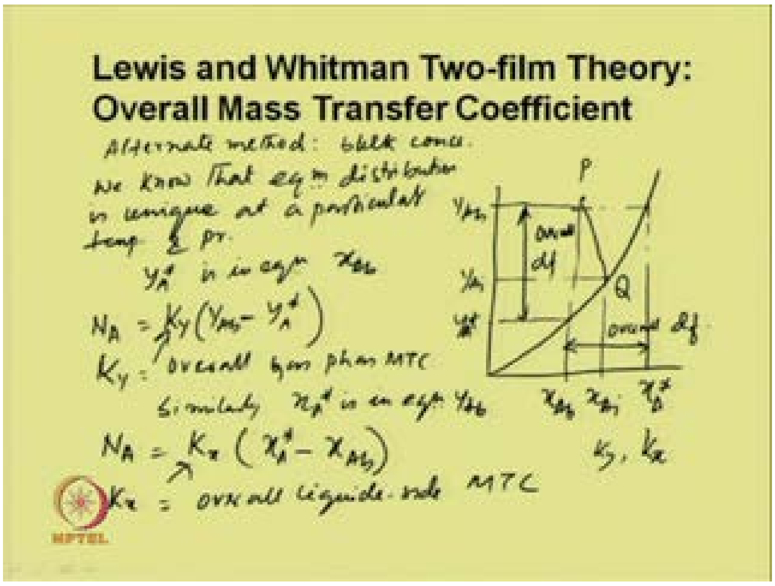

Lewis and Whitman Two-film Theory: Overall Mass Transfer Coefficient

Alternate method: bulk conc.

we know that eqm distribution is unique at a particular temp & pr.

y_A^* is in eqm x_{Ab}

$N_A = K_y (y_{Ab} - y_A^*)$

K_y = overall gas phase MTC

Similarly x_A^* is in eqm y_{Ab}

$N_A = K_x (x_A^* - x_{Ab})$

K_x = overall liquid-side MTC

So, the alternate method is based on bulk concentration, we know that equilibrium distribution is unique at a particular temperature and pressure. So, y A star is in equilibrium with x A B. If we look into the previous equilibrium curve, suppose this is p, this is q, and this is the y A i, this is x A i, and this is x A B, and this is y A B. So, this is y A star, which is equilibrium with x A B. So, N A will be K y capital K y y A B minus y A star; K y overall gas phase mass transfer coefficient. Similarly, x A star is in equilibrium with y A B, so this is in equilibrium with x A star. So, we can write N A is equal to K x capital K x x A star minus x A B. So, this is the overall driving force in the liquid phase, and this is the overall driving force, overall driving force, and this is also overall driving force in the liquid phase, and this is in the gas phase x A B. So, K x is the overall liquid side mass transfer coefficient.

In the next class, we will discuss how to correlate between the overall mass transfer coefficient, capital K y and capital K x and between small k y, the individual mass transfer small k x individual mass transfer coefficient, and which is required to calculate the resistances between the phases. So, we will discuss in the next class.

Thank you.