Bioreactor Design and Analysis
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Lecture – 19
Mass Transfer in Bioreactors – Part 1

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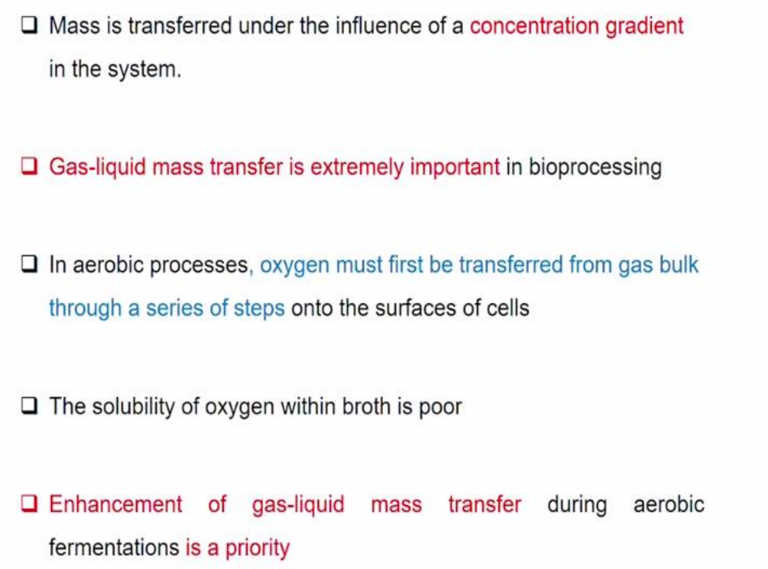

❑ Mass is transferred under the influence of a concentration gradient in the system.

❑ Gas-liquid mass transfer is extremely important in bioprocessing

❑ In aerobic processes, oxygen must first be transferred from gas bulk through a series of steps onto the surfaces of cells

❑ The solubility of oxygen within broth is poor

❑ Enhancement of gas-liquid mass transfer during aerobic fermentations is a priority

Let us begin with the next topic, which is mass transfer in bioreactors. Now, mass is transferred we know under the influence of a concentration gradient in a system, the driving force is the concentration gradient. The gas-liquid mass transfer, this is extremely important in bioprocessing. In aerobic processes, oxygen must first be transferred from gas bulk through a series of steps onto the surface of cells.

The solubility of oxygen within the broth is very poor. Generally, these broths are aqueous systems and oxygen solubility in aqueous systems is poor. Enhancement of gas-liquid mass transfer therefore becomes the crucial steps especially in aerobic fermentations.

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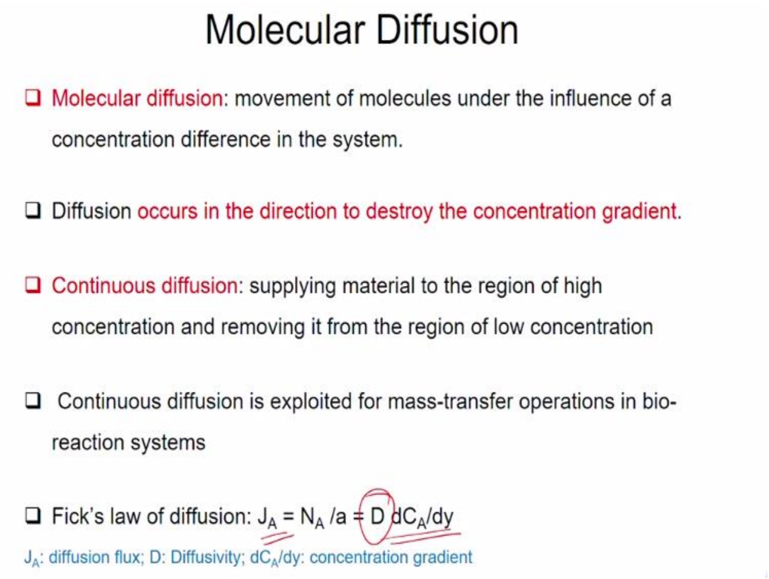

Molecular Diffusion

- ☐ Molecular diffusion: movement of molecules under the influence of a concentration difference in the system.
- ☐ Diffusion occurs in the direction to destroy the concentration gradient.
- ☐ Continuous diffusion: supplying material to the region of high concentration and removing it from the region of low concentration
- ☐ Continuous diffusion is exploited for mass-transfer operations in bio-reaction systems
- ☐ Fick's law of diffusion: $J_A = N_A /a = D\, dC_A/dy$

J_A: diffusion flux; D: Diffusivity; dC_A/dy: concentration gradient

Now, we need to first understand how does oxygen get dissolved in the bulk liquid in a fermenter. Now, before we understand that let us do a brush up with the phenomenon of molecular diffusion. We all know that molecular diffusion involves movement of molecules under the influence of a concentration difference in the system. Diffusion occurs in the direction to destroy this concentration gradient.

So, for a continuous diffusion to happen supplying material to the region of high concentration and removing it from the region of low concentration can keep the diffusion process continuous. This continuous diffusion is what which is exploited for mass transfer operations in bioreaction systems. So, in order to quantify mass transfer rates, we will apply Fick's law of diffusion.

We all know what is Fick's law of diffusion. As shown on the slide, this is the mass flux which is related to the concentration gradient where the coefficient of relationship is your diffusivity. So, J A stands for the diffusive flux, D is for your diffusivity and dC A by dy your concentration gradient.

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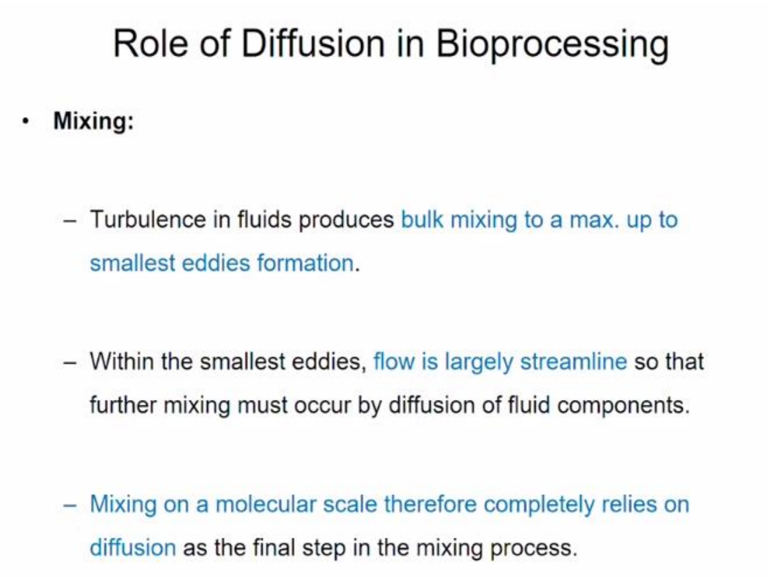

Role of Diffusion in Bioprocessing

- **Mixing:**
  - Turbulence in fluids produces bulk mixing to a max. up to smallest eddies formation.
  - Within the smallest eddies, flow is largely streamline so that further mixing must occur by diffusion of fluid components.
  - Mixing on a molecular scale therefore completely relies on diffusion as the final step in the mixing process.

Now, let us see what is the role of diffusion in bioprocessing. First is mixing. So, turbulence in fluids produces bulk mixing to maximum up to the smallest eddy formation. Within the smallest eddy, the flow is largely we can assume streamline, so that further mixing occurs only by diffusion of the fluid components. Now mixing on a molecular scale therefore completely relies on diffusion as the final step in the mixing process.

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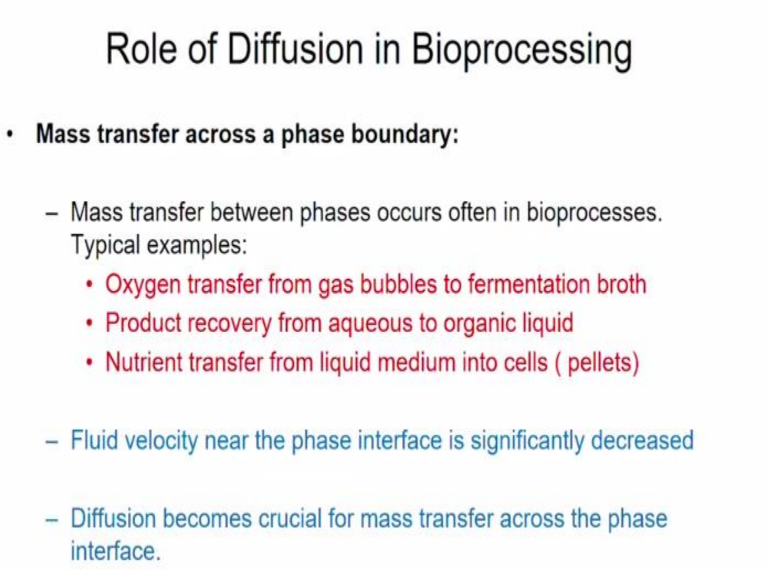

Role of Diffusion in Bioprocessing

- **Mass transfer across a phase boundary:**
  - Mass transfer between phases occurs often in bioprocesses. Typical examples:
    - Oxygen transfer from gas bubbles to fermentation broth
    - Product recovery from aqueous to organic liquid
    - Nutrient transfer from liquid medium into cells (pellets)
  - Fluid velocity near the phase interface is significantly decreased
  - Diffusion becomes crucial for mass transfer across the phase interface.

Now, let us understand the mass transfer across the phase boundary because oxygen for example is being transferred from the gas bubbles to the liquid broth and then to the cells. So, mass transfer between phases occurs in bioprocesses at various steps. Let us take some examples like for example oxygen I said earlier is transferred from gas bubble to the fermentation broth.

The second product recovery again mass transfer is involved from aqueous to organic liquid in case of solvent extractions. The nutrient transfer from liquid medium to the cells which are in the form of pellet. So, which means from the outer layer to the inner most cell. Now fluid velocities near the phase interface, they are significantly decreased because of the boundary layer. Now diffusion becomes therefore very crucial for mass transfer across these phases or interface.

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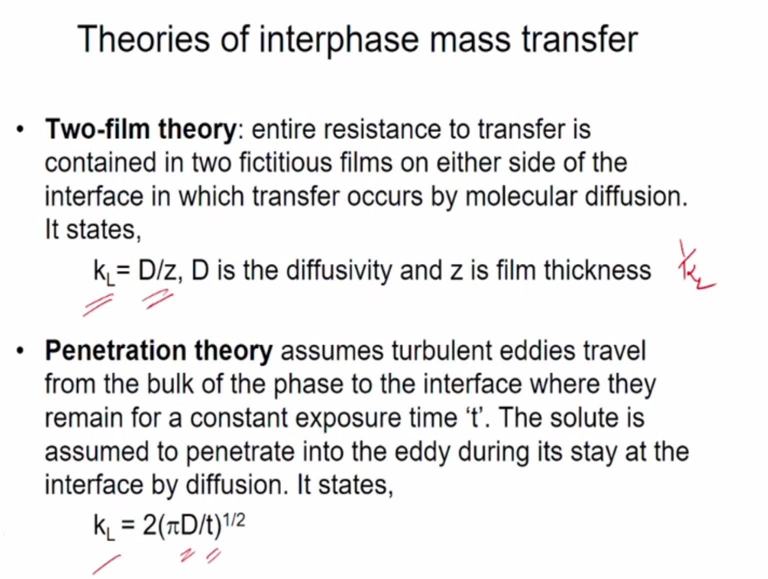

Theories of interphase mass transfer

- **Two-film theory**: entire resistance to transfer is contained in two fictitious films on either side of the interface in which transfer occurs by molecular diffusion. It states,

  $k_L = D/z$, D is the diffusivity and z is film thickness $\frac{1}{k_L}$

- **Penetration theory** assumes turbulent eddies travel from the bulk of the phase to the interface where they remain for a constant exposure time 't'. The solute is assumed to penetrate into the eddy during its stay at the interface by diffusion. It states,

  $k_L = 2(\pi D/t)^{1/2}$

Here to explain this mass transfer across the interface, there are various theories. We will be focusing here on the two-film theory where the entire resistance to transfer is assumed to be contained in the two fictitious films on either side of the phase interface in which the transfer will occur only by molecular diffusion. And this resistance is set to be related to the diffusivity and the film thickness as shown here.

So, your resistance which is 1 by k L, k L is your mass transfer coefficient, is related to your diffusivity and the thickness of that film. Penetration theory is another theory, which assumes that there are turbulent eddies which travel from the bulk to the phase to the interface where they remain for a constant exposure time t. Now the solute is assumed to penetrate into the eddy during its stay at the interface by diffusion.

So, it states that your mass transfer coefficient is related to the diffusivity and the time for which these small eddies stay at the interface.

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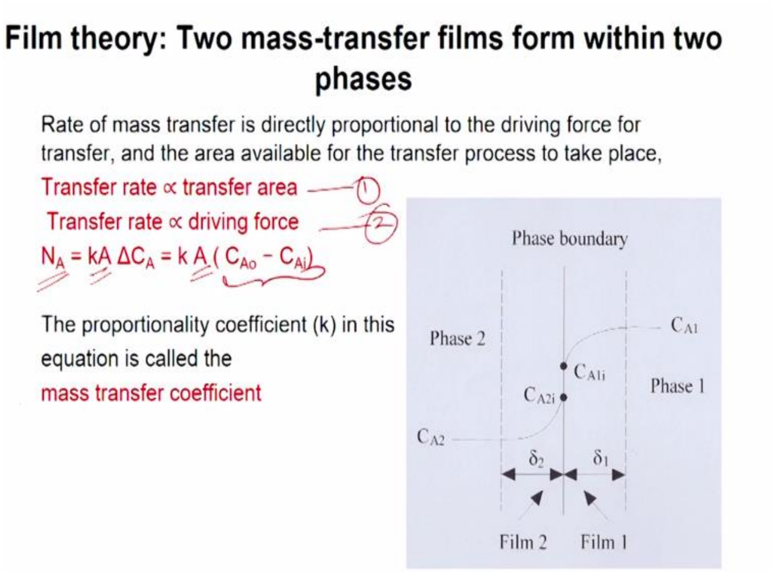

Film theory: Two mass-transfer films form within two phases

Rate of mass transfer is directly proportional to the driving force for transfer, and the area available for the transfer process to take place,

Transfer rate ∝ transfer area ①

Transfer rate ∝ driving force ②

$N_A = kA\,\Delta C_A = k\,A\,(C_{Ao} - C_{Ai})$

The proportionality coefficient (k) in this equation is called the mass transfer coefficient

So, as I said earlier we will assume two-film theory to explain the mass transfer in the gas-liquid interface. So, to generalize the rate of mass transfer we know is directly proportional to the driving force for the transfer and in this case the driving force is the concentration difference. So, it is directly proportional to the driving force and also to the area which is available for the transfer to happen.

So, your mass transfer rate as given here in the first line is proportional to the transfer area and the transfer rate is again proportional to the driving force which is concentration difference here. So, your mass transfer rate it is called as mass transfer proportionality coefficient, which we call it as mass transfer coefficient, your surface area for transfer and your concentration gradient across the interface. Now the proportionality constant as I said is called the mass transfer coefficient.

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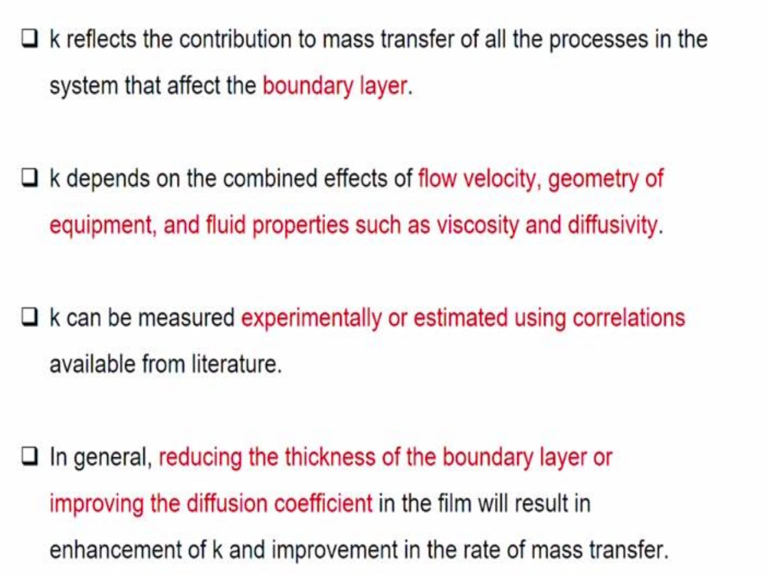

- ❑ k reflects the contribution to mass transfer of all the processes in the system that affect the boundary layer.
- ❑ k depends on the combined effects of flow velocity, geometry of equipment, and fluid properties such as viscosity and diffusivity.
- ❑ k can be measured experimentally or estimated using correlations available from literature.
- ❑ In general, reducing the thickness of the boundary layer or improving the diffusion coefficient in the film will result in enhancement of k and improvement in the rate of mass transfer.

So, now k here It reflects the contribution to mass transfer of all the processes in the system that are affecting this boundary layer. The k therefore depends on the combined effects of flow velocity, geometry of the equipment, fluid properties like for example viscosity and diffusivity. Now again k is measured experimentally or can also be estimated using correlations empirical correlations available in literature.

In general what is observed is that as we reduce the thickness of the boundary layer or if we improve the diffusion coefficient in the film, it will result in the enhancement of the mass transfer coefficient. So, the mass transfer coefficient by two-film theory if you remember was directly proportional to the diffusivity and inversely proportional to the film thickness. And once the k is improved, your mass transfer rate is also improved.

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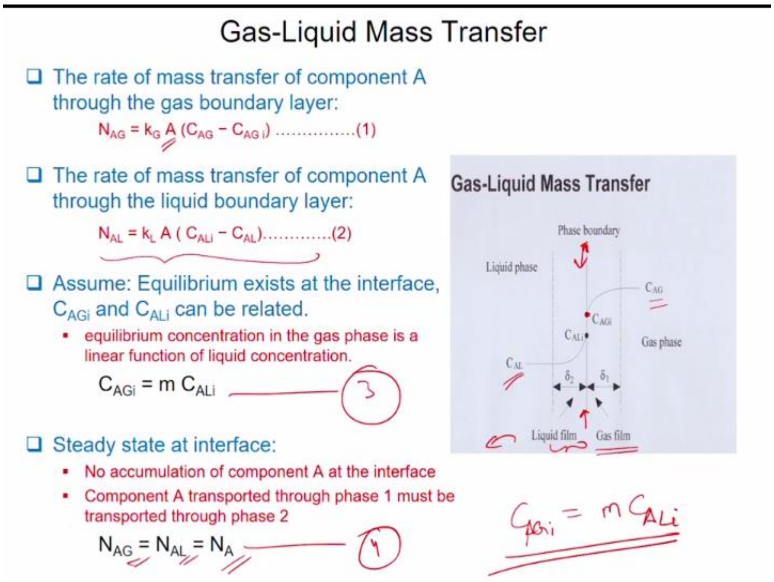

Gas-Liquid Mass Transfer

- ❑ The rate of mass transfer of component A through the gas boundary layer:

$$N_{AG} = k_G A (C_{AG} - C_{AGi}) \ldots\ldots\ldots\ldots\ldots(1)$$

- ❑ The rate of mass transfer of component A through the liquid boundary layer:

$$N_{AL} = k_L A (C_{ALi} - C_{AL}) \ldots\ldots\ldots\ldots(2)$$

- ❑ Assume: Equilibrium exists at the interface, C_{AGi} and C_{ALi} can be related.
  - equilibrium concentration in the gas phase is a linear function of liquid concentration.

$$C_{AGi} = m\,C_{ALi} \text{ ——— } ③$$

- ❑ Steady state at interface:
  - No accumulation of component A at the interface
  - Component A transported through phase 1 must be transported through phase 2

$$N_{AG} = N_{AL} = N_A \text{ ——— } ④$$

$C_{AGi} = m\,C_{ALi}$

So, now let us derive some expressions to explain the gas-liquid mass transfer. So, the rate of mass transfer of component A, so if you see this schematic here, let us see the diagram where A is your entity which is transferring from the gas phase to the liquid phase. So, C AG stands for the concentration of that component A in the gas phase, bulk of the gas phase. Then as it crosses the boundary layer, the gas film, so there are two fictitious films across the interface.

This is the phase boundary, which I am showing with the red color arrow. So, you are C AG it drops to some equilibrium value, which we call it as C AGi. And then again further traveling across phasing the resistance C AL is the concentration of A in the bulk of the liquid after getting transferred. So, the rate of mass transfer of component A through the boundary layer, the gas boundary layer, which is written as gas film here in the diagram can be given as equation 1.

So, k G stands for the mass transfer coefficient of the gas film, C AG is your component A concentration in the gas bulk and C AGi is the component A concentration at the interface and capital A is the surface area. So, now equation one demonstrates the rate of mass transfer of component A across the gas film. Now, we will assume that steady state prevails at the boundary at the interface.

So, no accumulation of A is happening which would mean that the rate at which the A is getting transferred through this gas film should be equal to the rate at which the A is further getting transferred through the liquid film to the liquid bulk. So, for the rate of mass transfer of component A through the liquid boundary layer we can use the expression given in equation 2.

So, similar to equation 1 your equation 2 stands for the rate of mass transfer through the liquid boundary layer where C ALi is the concentration of component A in liquid at the interface, C AL is the concentration of component A in the liquid bulk. Now because no accumulation is happening, so we assume equilibrium is existing at the interface. Then we assume that equilibrium is existing.

Which means that at the interface C AGi which is the concentration in gas is related to C ALi which is the concentration of component A in liquid at the interface by a constant m, they are linearly related. So, if you remember this law is Henry's law. Now equilibrium concentration in the gas phase is a linear function of that in the liquid phase or liquid concentration. So, as I said this is the linear relationship of the equilibrium concentrations.

Now we are assuming steady state prevails. So, therefore no accumulation of component A at the interface. So, this means that component A is transported through phase one which is the gas phase here must be transported through phase two. So, the rate of transfer through the gas here shown in 4 is equal to the rate of transfer from the liquid both should be equal, so had been designated N A, so G and L have been removed as both are equal.

So, the idea now is in order to find an expression for this mass transfer rate of component A through the interface, it is very difficult to measure the concentration values be it in gas or liquid at the phase boundary. So, we would like to remove the nonmeasurable quantities from these equations and derive an expression for the mass transfer across this boundary layer or across this film.

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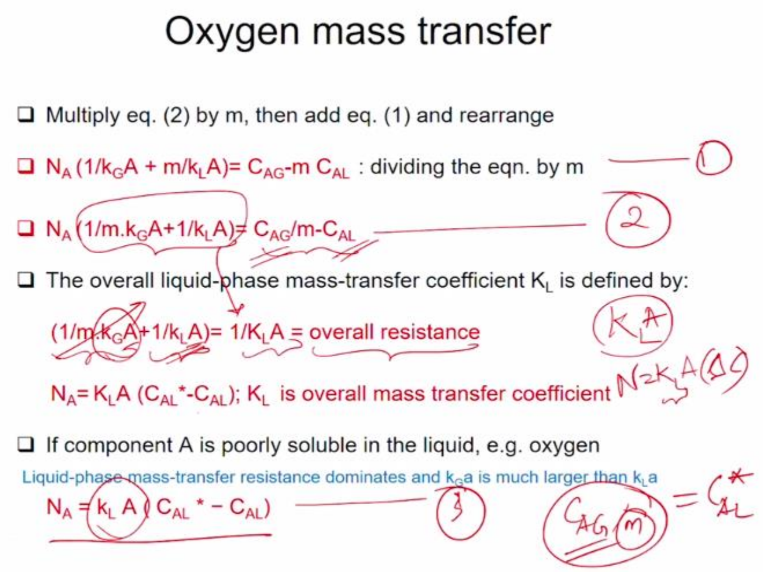

Oxygen mass transfer

- Multiply eq. (2) by m, then add eq. (1) and rearrange
- $N_A (1/k_G A + m/k_L A) = C_{AG} - m\, C_{AL}$: dividing the eqn. by m ——— ①
- $N_A (1/m.k_G A + 1/k_L A) = C_{AG}/m - C_{AL}$ ——— ②
- The overall liquid-phase mass-transfer coefficient K_L is defined by:

  $(1/m.k_G A + 1/k_L A) = 1/K_L A$ = overall resistance $K_L A$

  $N_A = K_L A (C_{AL}^* - C_{AL})$; K_L is overall mass transfer coefficient $N = K_L A (\Delta C)$
- If component A is poorly soluble in the liquid, e.g. oxygen

  Liquid-phase mass-transfer resistance dominates and $k_G a$ is much larger than $k_L a$

  $N_A = k_L A (C_{AL}^* - C_{AL})$ ——— ③ $C_{AG}/m = C_{AL}^*$

So, if you multiply equation 2 here which explains the rate of mass transfer of component A through the liquid boundary layer. So, if we multiply this by m, so m into C ALi we know can be replaced as C AGi and so m into C Ali. So we will multiply this entire equation by m and if we then add after multiplication the equation 1 and this is now can be written as N A. Then and if we bring all the constants together and the variables on one side, we end up in this equation.

So, once we divide the entire equation after addition by m, we end up here, let us call this as first equation and this one is second. All terms in the bracket in equation 2, they are all constants. So, let us replace this as the overall resistance and the liquid phase mass transfer coefficient by capital K subscript L. So, now if you see the right hand side is a function of the gas phase component A concentration bulk gas phase concentration and the bulk liquid phase concentration of component A.

And in the LHS this entire constant is replaced by a constant 1 by k L and A has been kept brought out and kept common. So, this we can call it as overall resistance like if you remember k L times A into concentration difference was your rate of mass transfer and this is called resistance k L A. So, here this entire thing has been replaced as capital K L A. So, this is overall resistance.

So, then your N A the mass transfer rate of A can be given as K L A times C AL star – C AL. Now, C AL star is nothing but the equilibrium concentration of the component A in gas with the liquid governed by the Henry's constant m. So, this has been replaced as a liquid phase corresponding liquid phase concentration which is in equilibrium with the C AG gas bulk concentration.

So, this is your saturation concentration of component A in liquid and C AL is your bulk liquid concentration of component A and K L is called as the overall mass transfer coefficient. So, for component A which is sparingly soluble in liquid like for example in case of oxygen, then your liquid phase mass transfer resistance dominates, which is 1 by small k L A and your 1 by k G A, which is the gas phase mass transfer resistance is very less in comparison to k L A.

Now, because 1 by k G A is very less, which is the resistance of the gas phase so your k G A value is very very high than k L A. So, this is neglected and your capital K L A can be replaced as small k L A in this. So, this equation holds true for sparingly soluble components in the fermentation system. So, this is how we can define the oxygen transfer rate.