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Mass Transfer-I

Mass Transfer Theories

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Mass Transfer Theories

Mass Transfer Theories

A number of theories have been developed to visualize the mass transfer mechanism and proposing the expression for the mass transfer coefficient. Some important and commonly used theories are listed bellow

1. Film theory
2. Penetration theory
3. Boundary layer theory
4. Two-film theory
5. Surface renewal theory
6. Surface stretch theory

Film theory

- This is the oldest mass transfer theory similar to heat transfer.
- Basic concept – the resistance to diffusion can be considered equivalent to that in stagnant film of a certain thickness
- Often used as a basis for complex problems of multicomponent diffusion or diffusion plus chemical reaction.

Assumptions

- Laminar flow (layer) near the wall
- Mass transfer is mainly by molecular diffusion
- Flow and mass transfer occurs in a thin film at the interface
- Steady state flux across film
- The concentration gradient almost linear
- As the distance from the wall increases, turbulent become stronger.
- The resistance to mass transfer is mainly in laminar boundary layer.

The above assumptions are satisfactory for the practical situations where mass transfer occurs at low concentrations and/ or low flux

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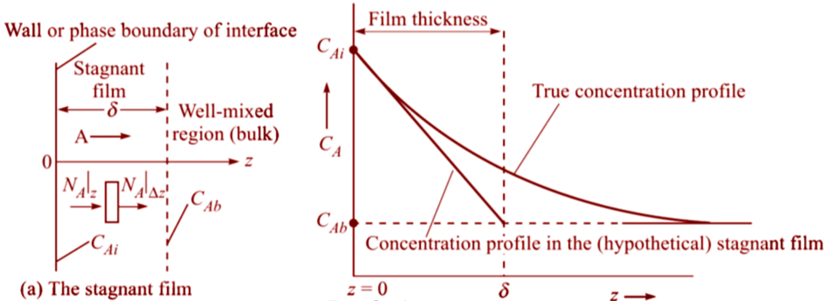
Considering turbulent flow over a solid surface and a simultaneous mass transfer is taking place.



(a) The stagnant film

C_{Ai} = conc. at the interface

C_{Ab} = conc. at the bulk

(Interface)

(b) Concentration profiles of the solute near the phase boundary (δ indicates the edge of the film)

Cont…

The basic concept of the film theory is that the resistance to diffusion can be considered equivalent to that in a stagnant film of a certain thickness

$$N_A = -D_{AB}\left[\frac{dC_A}{dz}\right]_{z=0} = \frac{D_{AB}}{\delta}(C_{Ai} - C_{Ab})$$

the mass transfer coefficient is

$$k_L = \frac{D_{AB}}{\delta}$$

$$k_L \propto D_{AB}$$

Where,
N_A = Mass Transfer flux
D_{AB} = Mass diffusivity
k_L = Mass transfer coefficient

Examples:
Evaporation, Gas scrubbing, etc.

Film theory is valid for the following conditions when

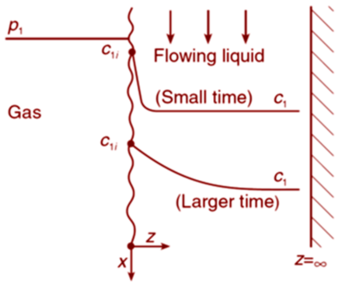
- The mass transfer flux is small (low)
- The mass transfer occurs at low concentrations or the mass transfer occurs by equimolar counter diffusion.
- All fluid characteristics are unimportant in the film thickness

Penetration Theory (Higbie, 1935)

Assumptions

In addition of "Film Theory" assumptions

- Flow and mass transfer occurs in a **very thick film** at the interface
- Molecular diffusion is important along the film thickness
- Convection is important along the flow direction
- Unsteady state mass transfer occurs to a liquid elements as long as it is in the contact with the interphase (other phase)
- Liquid elements (each) stays in contact with gas (or other phase) for the same period of time.
- The time of exposure for the mass transfer is too short



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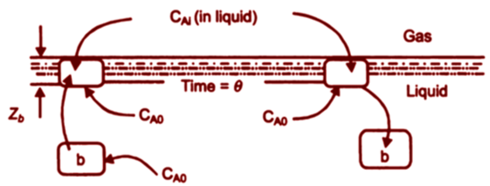
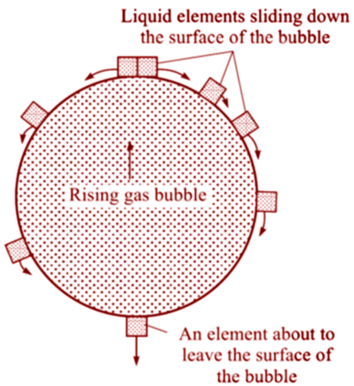




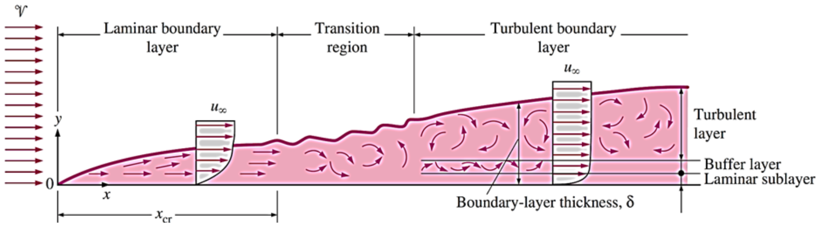
Instantaneous mass transfer coefficient, $k_L = \sqrt{\frac{D_{AB}}{\pi t}}$

Average mass transfer coefficient, $k_{L,av} = 2\sqrt{\frac{D_{AB}}{\pi t_c}}$

$$k \propto D_{AB}^{0.5}$$

Boundary layer theory

- Mass transfer often take place in a thin boundary layer near a surface where the fluid is in laminar flow.
- The coefficient, k_c depends on 2/3 power of diffusivity and decreases with increasing distance along the surface in the direction of flow
- Boundary layer theory can be used to estimate k_c for some situations,
- but exact prediction of k_c cannot be made when the boundary layer become turbulent.



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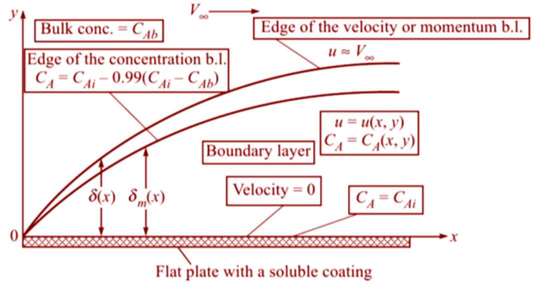
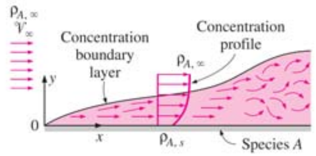




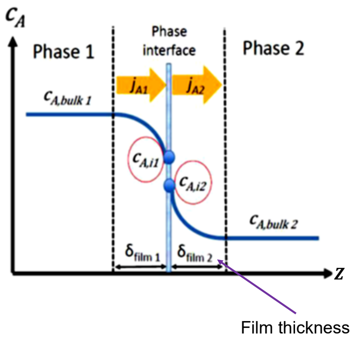
$$\frac{Nu}{Re_x Pr^{1/3}} = \frac{Sh}{Re_x Sc^{1/3}} = \frac{f}{2} = 0.332\, Re_x^{-1/2}$$

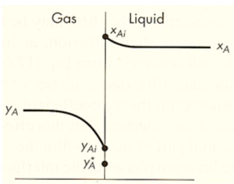
Where,
- f = Friction factor
- Nu = Nusselt number
- Pr = Prandtl number
- Sc = Schmidt number
- Re = Reynolds number
- Sh = Sherwood number

$$\boxed{k \propto D_{AB}^{2/3}}$$

Two-film theory

- On two sides of the interface, there exist two effective films of certain thickness, component *A* passes through these two film by molecular diffusion.
- At the interface, the gas is in equilibrium with liquid.
- The concentration gradients in the two bulk phases equal to zero.

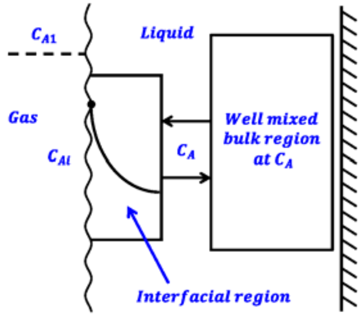




Surface renewal theory (Danckwert's theory, 1951)

In surface renewal theory,

- The thick film framework is replaced by **Two** regions
  - ➢Interface
  - ➢Bulk
- In the interfacial region mass transfer takes place according to penetration theory.
- Then elements of this region **Are Exchanged** with the bulk region.
- This is the so-called surface renewal process and based upon **"distribution of age".**



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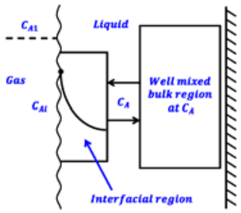
Assumptions

1. The liquid elements at the interphase are being randomly replaced by fresh elements from the bulk.
2. At any moment each of the liquid elements at the surface has the same probability of being replaced by a fresh element.
3. Unsteady state mass transfer occurs to an element during its stay at the interface.



$$k_L = \sqrt{D_{AB} s}$$

Where, s is the friction of surface area renewed per unit time

$$k \propto D_{AB}^{0.5}$$

The major contribution of the surface renewal theory is that it gives a more REALISTIC physical situation. This gives a better starting point for development of effective correlations and better models.

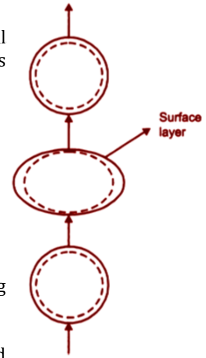
Surface stretch theory

The **surface stretch theory** is the extension of the penetration-surface renewal concept where the interfacial surface through which mass transfer occurs periodically with time.

Example:

liquid drop rising through a denser liquid.

- Drop will move or cause to move unsteadily from side to side (wobbles).
- Drop will change the shape, oscillate, etc.
- The central portion of the drop is thoroughly turbulent.
- The mass transfer resistance of the drop resides in a surface layer of varying thickness.
- Similar situations occurs while drops and bubbles form at nozzles and when liquid surface are wavy or rippled.



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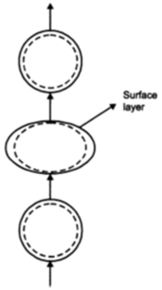
$$k_L = \frac{(A/A_r)\sqrt{D_{AB}/\pi\theta_r}}{\sqrt{\int_0^{\theta/\theta_r} (A/A_r)^2 \, d\theta}}$$



$$\boxed{k \propto D_{AB}^{0.5}}$$

Where,
A = time dependent interface
A_r = reference value of A surface
θ_r = Constant with dimensions of time, defined for each situation
e.g., for drop formation θ_r might be drop formation time

References

ETH
Mass Transfer
Theories for Mass Transfer Coefficients
Lecture 9, 15.11.2017, Dr. K. Wegner

- Lecture notes/ppt of Dr. Yahya Banat **(ybanat@qu.edu.qa)**