Transport Phenomena II

Lec 7: Mass Transfer Across Interfaces

Content

Introduction, Concentration Profiles in Interface, The Two-Film Theory, Overall Mass-Transfer Coefficients

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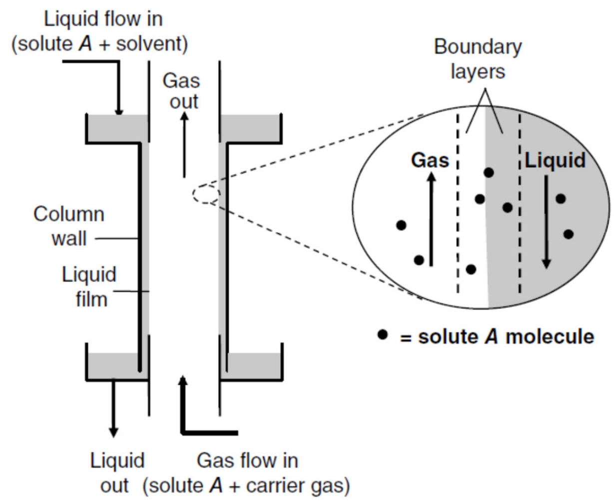
Content

- Introduction
- Concentration Profiles in Interface,
- The Two-Film Theory,
- Overall Mass-Transfer Coefficients

Introduction

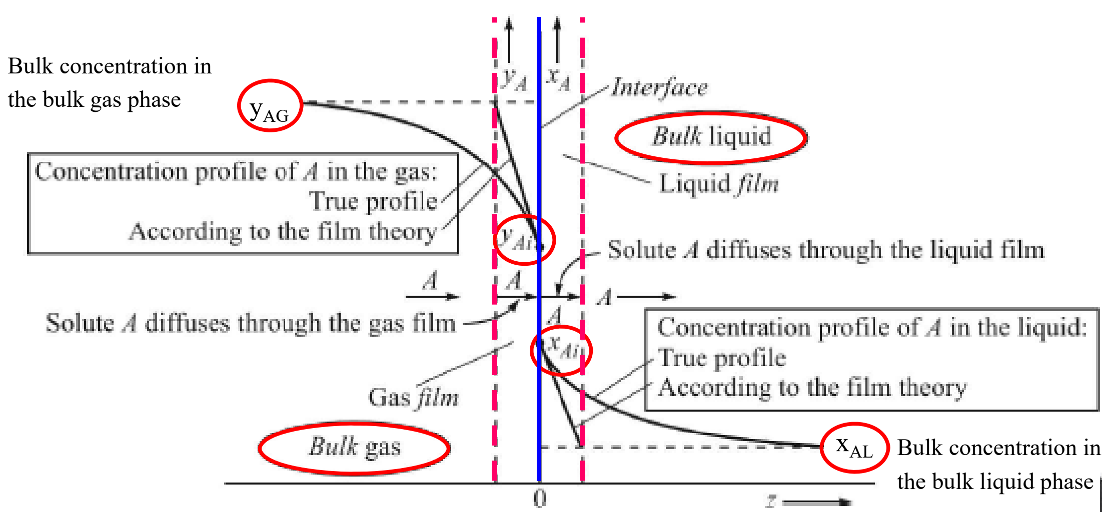
- Mass transfer between phases across the following interfaces are of great interest in separation processes:
  - Gas/liquid interface
  - Liquid/liquid interface
  - Fluid/solid interface
- Such interfaces are found in the following separation processes:
  - Absorption
  - Distillation
  - Extraction
  - Stripping



Concentration Profiles in Interface Mass Transfer

Mass transfer from one phase (say the gas phase, *G*) to another phase (say the liquid phase, *L*) involves the following sequential steps:

(a) The solute (*A*) is transported from the bulk of the gas phase (*G*) to the gas–liquid interface.
(b) The solute (*A*) is picked up or absorbed by the liquid phase (*L*) at the gas–liquid interface.
(c) The absorbed solute (*A*) is transported from the interface to the bulk of the liquid (*L*).



Concentration Profiles in Interface Mass Transfer

- The concentration in the bulk gas phase y_{AG} or (y_{Ab}) decreases to y_{Ai} at the interface.
- The liquid concentration starts at x_{Ai} at the interface and falls to x_{AL} or (x_{Ab})
- Since there would be no resistance to transfer across this interface, then the interfacial concentrations (y_{Ai} and x_{Ai}) are related by the ***equilibrium distribution relation.***

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

- For gas-liquid system in which mass transfer of A from a gas, across an interface, and into a liquid (at low concentrations).

$$p_{Ai} = Hx_{Ai} \qquad \text{Henry's law equation}$$

where H is the Henry's law constant in atm/mole fraction for the given system

Concentration Profiles in Interface Mass Transfer

- The relation can be also written as:

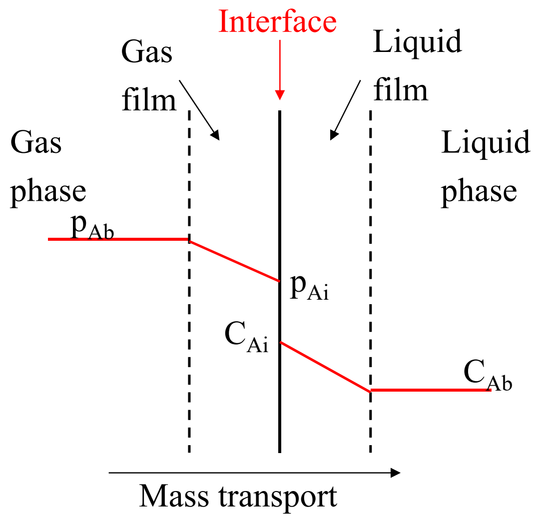
$$y_{Ai} = H^{'} x_{Ai}$$

Where $H^{'} = H / P$ and dependent on the total pressure

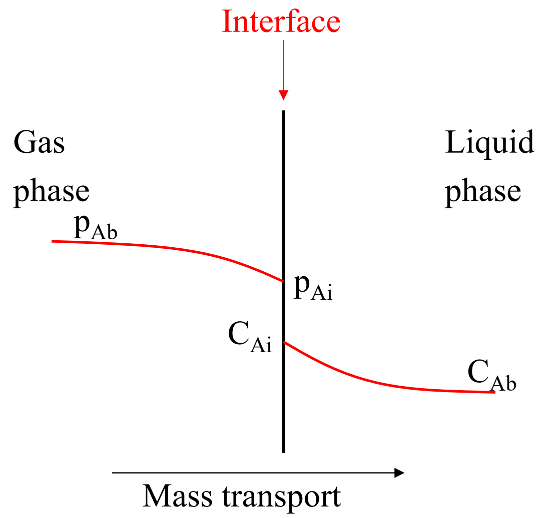
The Two-Film Theory

- Gas–liquid and liquid–liquid separation processes involve two fluid phases in contact and require consideration of mass-transfer resistances in both phases.
- Lewis and Whitman (1924) visualized that two stagnant fluid films exist on either side of the interface and mass transfer occurs through these films in series.
- Each film presents a resistance to mass transfer, but concentrations in **the two fluids at the interface are assumed to be in phase equilibrium**. That is, there is no additional interfacial resistance to mass transfer.

The Two-Film Theory



Concentration gradients for the film theory



More realistic concentration gradients

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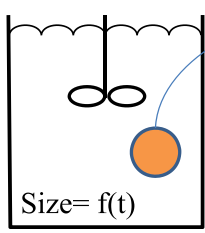
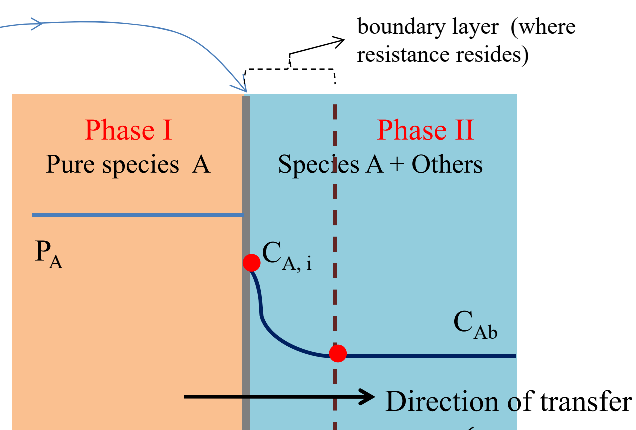
The solution is at constant composition except near the bubble surface





interface

bulk

Flux of mass transfer for species A

$$N_A = k_c (C_{A,i} - C_{Ab})$$

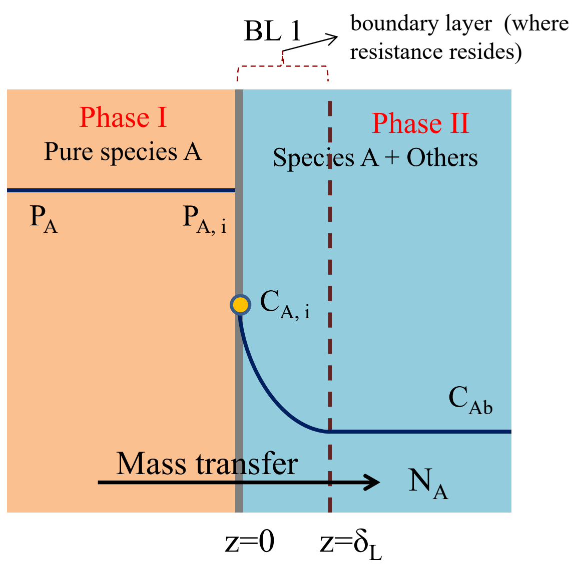
Mass transfer coefficient; represents the rate constant for moving species from boundary into the bulk of the phase. Unit varies according to the unit of driving force

Concentration of species A in phase II (bulk value)

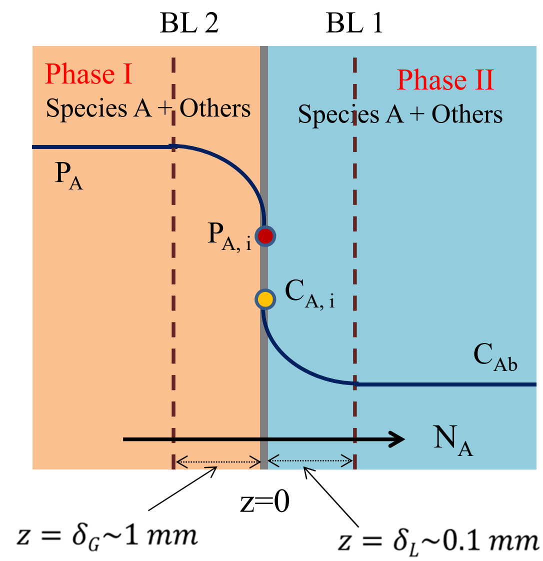
Maximum concentration achievable in phase II; normally the concentration in equilibrium with phase I

Mass is transferred from one phase to another through an interface

Pure to Mixture



Mixture to Mixture



Two Film Theory Applied at Steady-State

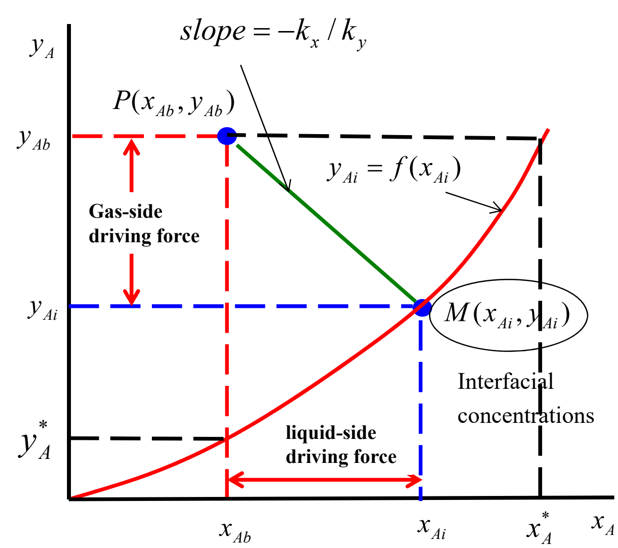
- Consider steady-state mass transfer of A from a gas, across an interface, and into a liquid.

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

Gas-phase flux to the interface — Liquid-phase flux from the interface

- Using the above equation, We may write

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



Example

Interface Compositions in Interphase Mass Transfer

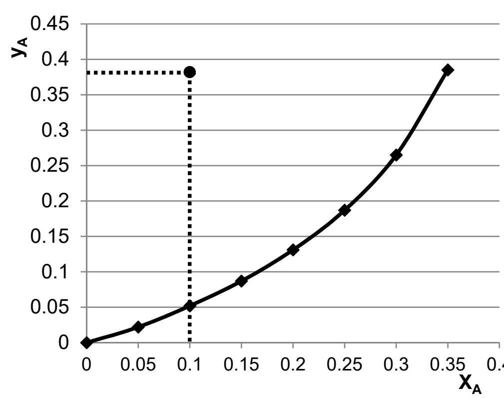
The solute A is being absorbed from a gas mixture of A and B in a wetted-wall tower with the liquid flowing as a film downward along the wall. At a certain point in the tower the bulk gas concentration $y_{AG} = 0.380$ mol fraction and the bulk liquid concentration is $x_{AL} = 0.100$. The tower is operating at 298 K and 1.013×10^5 Pa and the equilibrium data are as follows:

x_A	y_A	x_A	y_A
0	0	0.20	0.131
0.05	0.022	0.25	0.187
0.10	0.052	0.30	0.265
0.15	0.087	0.35	0.385

Example Contd

The solute A diffuses through stagnant B in the gas phase and then through a nondiffusing liquid.

Using correlations for dilute solutions in wetted-wall towers, the film mass-transfer coefficient for A in the gas phase is predicted as $k'_y = 1.465 \times 10^{-3}$ kg mol A/s · m² · mol frac (1.08 lb mol/h · ft² · mol frac) and for the liquid phase as $k'_x = 1.967 \times 10^{-3}$ kg mol A/s · m² · mol frac (1.45 lb mol/h · ft² · mol frac). Calculate the interface concentrations y_{Ai} and x_{Ai} and the flux N_A.



Example Contd

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Example Contd

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Example Contd

Overall Mass-Transfer Coefficients

- Interfacial concentrations are not directly measurable quantities (sampling at the interface is not possible) and can not be specified in several practical problems.
- It is necessary to develop and approach to calculate the mass transfer rate based on the bulk concentrations.
- The overall mass-transfer coefficient based on the gas phase is defined by

$$K_y = \frac{N_A}{y_{Ab} - y_A^*}$$

where K_y is based on the overall gas-phase driving force in kg mol/s . m^2. mol frae, and y_A^* is the value that would be in equilibrium with x_{Ab}

- Also, the overall mass-transfer coefficient based on the liquid phase is defined by

$$K_x = \frac{N_A}{x_A^* - x_{Ab}}$$

Overall Mass-Transfer Coefficients

where K_x is based on the overall liquid-phase driving force in kg mol/s . m^2. mol frae, and x_A^* is the value that would be in equilibrium with x_{Ab}

- Therefore,

$$N_A = k_y(y_{Ab} - y_{Ai}) = k_x(x_{Ai} - x_{Ab}) = K_x(x_A^* - x_{Ab}) = K_y(y_{Ab} - y_A^*)$$

- Also,

$$y_{Ab} - y_A^* = \frac{N_A}{K_y} \qquad \text{and} \qquad x_A^* - x_{Ab} = \frac{N_A}{K_x}$$

$$x_{Ai} - x_{Ab} = \frac{N_A}{k_x}$$

$$y_{Ab} - y_{Ai} = \frac{N_A}{k_y}$$

Overall Mass-Transfer Coefficients

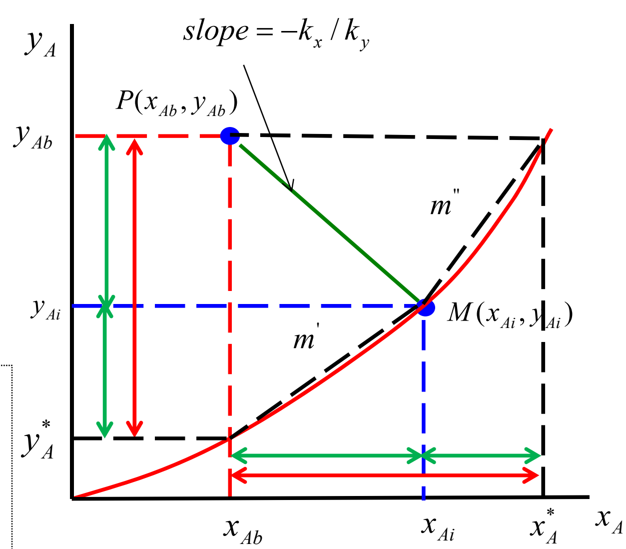
Non-Linear Equilibrium

- Considering the figure

$$m' = \frac{y_{Ai} - y_A^*}{x_{Ai} - x_{Ab}}$$

and

$$m'' = \frac{y_{Ab} - y_{Ai}}{x_A^* - x_{Ai}}$$



- Also

$$y_{Ab} - y_A^* = (y_{Ab} - y_{Ai}) + (y_{Ai} - y_A^*)$$

and

$$x_A^* - x_{Ab} = (x_{Ai} - x_{Ab}) + (x_A^* - x_{Ai})$$

Overall Mass-Transfer Coefficients

$$\longrightarrow \quad y_{Ab} - y_A^* = (y_{Ab} - y_{Ai}) + m'(x_{Ai} - x_{Ab})$$

hence

$$\frac{N_A}{K_y} = \frac{N_A}{k_y} + \frac{m' N_A}{k_x} \quad \longrightarrow \quad \frac{1}{K_y} = \frac{1}{k_y} + \frac{m'}{k_x}$$

$1/K_y$, can be considered to be the 'overall mass transfer resistance' *on the gas-phase basis*

It is the sum of the individual mass transfer resistances of the two phases

$\frac{1}{k_y}$ = individual gas-phase mass transfer resistance

$\frac{m'}{k_x}$ = individual liquid-phase mass transfer resistance (*on gas phase basis*)

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Overall Mass-Transfer Coefficients

Also,

The fractional resistance offered by the gas-phase

$$= \frac{\text{resistance offered by the gas-phase}}{\text{total resistance of the two phases}} = \frac{1/k_y}{1/K_y}$$

The fractional mass transfer offered by the liquid-phase

$$= \frac{\text{resistance offered by the liquid-phase}}{\text{total resistance of the two phases}} = \frac{m'/k_x}{1/K_y}$$

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Overall Mass-Transfer Coefficients

- The values of the m' is very important:
  - If m' is quite small, so that the equilibrium curve in the previous figure is almost horizontal, a small value of y_A in the gas will give a large value of x_A in equilibrium in the liquid.
  - The gas solute A is then very soluble in the liquid phase (absorption of ammonia in water), and hence the term m'/k_x is very small
  - The major resistance is in the gas phase, or the gas phase is controlling.

$$\longrightarrow \quad \frac{1}{K_y} = \frac{1}{k_y}$$

  - If m' is large, the fraction liquid phase resistance become high and the rate of mass transfer is controlled by the liquid phase resistance .

Overall Mass-Transfer Coefficients

- In similar manner,

$$x_A^* - x_{Ab} = (x_{Ai} - x_{Ab}) + \frac{y_{Ab} - y_{Ai}}{m''}$$

$$\longrightarrow \quad \frac{N_A}{K_x} = \frac{N_A}{k_x} + \frac{N_A}{m'' k_y} \quad \text{or} \quad \frac{1}{K_x} = \frac{1}{k_x} + \frac{1}{m'' k_y}$$

$\frac{1}{K_x}$ can be considered to be the 'overall mass transfer resistance' *on liquid-phase basis*

It is the sum of the individual mass transfer resistances of the two phases

$\frac{1}{k_x}$ = individual liquid-phase mass transfer resistance

$\frac{1}{m'' k_x}$ = individual gas-phase mass transfer resistance (*on liquid-phase basis*)

Overall Mass-Transfer Coefficients

- when m'' is very large, the solute A is very insoluble in the liquid (systems for absorption of oxygen or CO_2 from air by water), $1/m''k_y$ becomes small, and the liquid phase is controlling

$$\Rightarrow \frac{1}{K_x} = \frac{1}{k_x}$$

- Note that

$$K_y = \frac{K'_y}{(1-y_A)_{\cdot M}} \qquad K_x = \frac{K'_x}{(1-x_A)_{\cdot M}}$$

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Overall Mass-Transfer Coefficients

Linear Equilibrium

- A relation between the overall mass-transfer coefficients and the individual phase mass-transfer coefficients can be obtained when the equilibrium relation is linear, as expressed by

$$p_{A,i} = H\, c_{AL,i}$$

Also

$$p_A^* = H\, c_{Ab} \quad \text{and} \quad p_A = H\, c_{Ab}^*$$

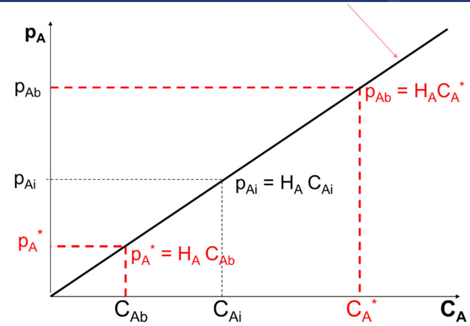
but

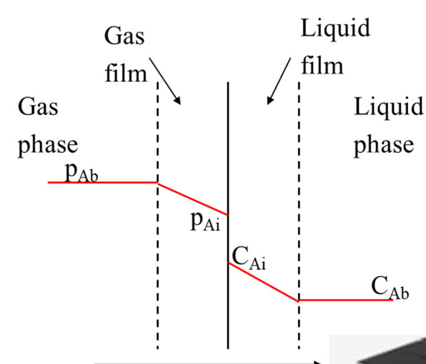
$$N_A = K_G(p_{Ab} - p_A^*)$$

Also

$$N_A = k_G(p_{Ab} - p_{A,i})$$

$$N_A = k_L(C_{Ai} - C_{Ab})$$





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Overall Mass-Transfer Coefficients

where

H_A is **Henry's constant for A**

p_{Ai} is the gas phase pressure and C_{Ai} is the liquid phase concentration.

- Unit of H: [Pressure]/[concentration] = [bar / (kg.m^3)]

- By making use of the above equations and with rearrangement

$$\frac{1}{K_G} = \frac{p_A - p_A^*}{N_A} = \frac{p_A - p_{A,i}}{N_A} + \frac{p_{A,i} - p_A^*}{N_A}$$

or

$$\frac{1}{K_G} = \frac{(p_A - p_{A,i})}{N_A} + \frac{H(c_{AL,i} - c_{Ab})}{N_A}.$$

$$\Rightarrow \quad \frac{1}{K_G} = \frac{1}{k_G} + \frac{H}{k_L}$$

Overall Mass-Transfer Coefficients

with $$N_A = K_L(c_{AL}^* - c_{Ab})$$

A similar expression for K_L may be derived as follows:

$$\frac{1}{K_L} = \frac{c_{AL}^* - c_{AL}}{N_A} = \frac{(c_{AL} - c_{AL,i})}{N_A} + \frac{(c_{AL,i} - c_{A,L})}{N_A} = \frac{(p_A - p_{A,i})}{H \cdot N_A} + \frac{(c_{AL,i} - c_{A,L})}{N_A}$$

$$\Rightarrow \quad \frac{1}{K_L} = \frac{1}{H \cdot k_G} + \frac{1}{k_L}$$

hence $$N_A = K_G(p_A - p_A^*) = \frac{p_{Ab} - H\,C_{Ab}}{H_A / k_L + 1 / k_G}$$

$$p_A^* = H\,c_{Ab}$$

$$\frac{1}{K_G}$$

Overall Mass-Transfer Coefficients

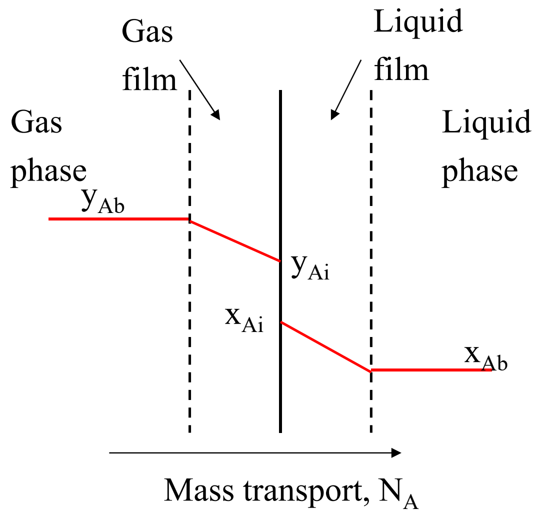
$N_A = K_y(y_A - y_A^*)$ and $N_A = K_x(x_A^* - x_A)$

with

$y_A^* = m \cdot x_A$ and $y_A = m \cdot x_A^*$

$$\Rightarrow \quad \frac{1}{K_y} = \frac{1}{k_y} + \frac{m}{k_x}$$

and $$\frac{1}{K_x} = \frac{1}{m \cdot k_y} + \frac{1}{k_x}$$



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Example

Using the same data as in Example 10.4-1, calculate the overall mass-transfer coefficient K_y', the flux, and the percent resistance in the gas and liquid films. Do this for the case of A diffusing through stagnant B.

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Example Contd

Example Contd

Example

In an experimental study of the absorption of ammonia by water in a wetted-wall column, the value of overall mass transfer coefficient, K_G was found to be 2.75×10^{-6} kmol/m^2-s-kPa. At one point in the column, the composition of the gas and liquid phases were 8.0 and 0.115 mole% NH_3, respectively. The temperature was 300K and the total pressure was 1 atm. Eighty five % of the total resistance to mass transfer was found to be in the gas phase. At 300 K, Ammonia –water solutions follows Henry's law upto 5 mole% ammonia in the liquid, with m = 1.64 when the total pressure is 1 atm. Calculate the individual film coefficients and the interfacial concentrations. Interfacial concentrations lie on the equilibrium line.

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Example Contd

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