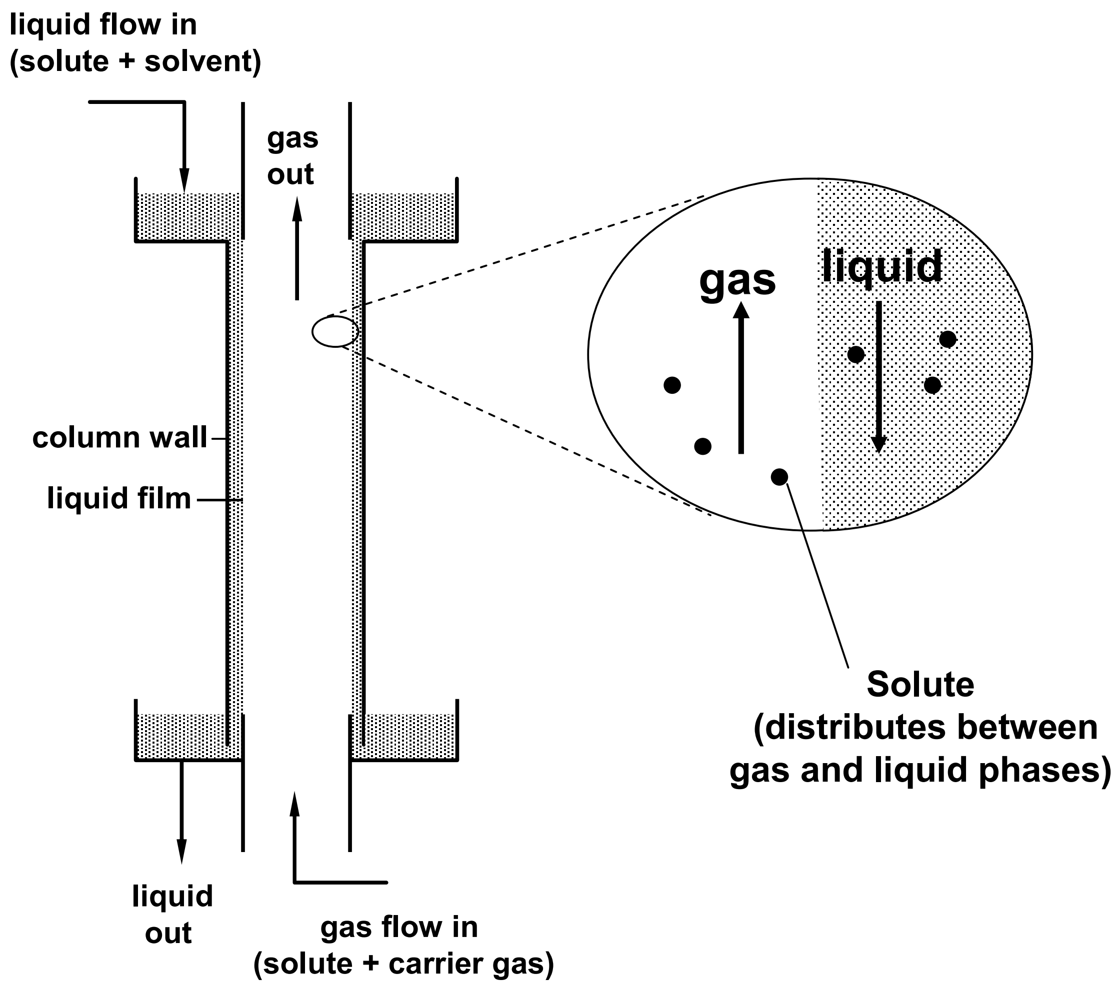
CHAPTER 29: CONVECTIVE MASS TRANSFER BETWEEN PHASES

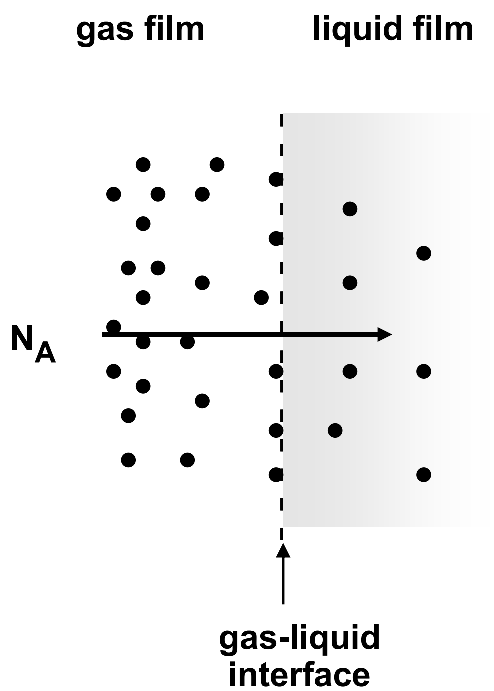
Introduction to Gas-Liquid Interphase Mass Transfer

The Wetted Wall Column
(a simple device to look at interphase mass transfer)

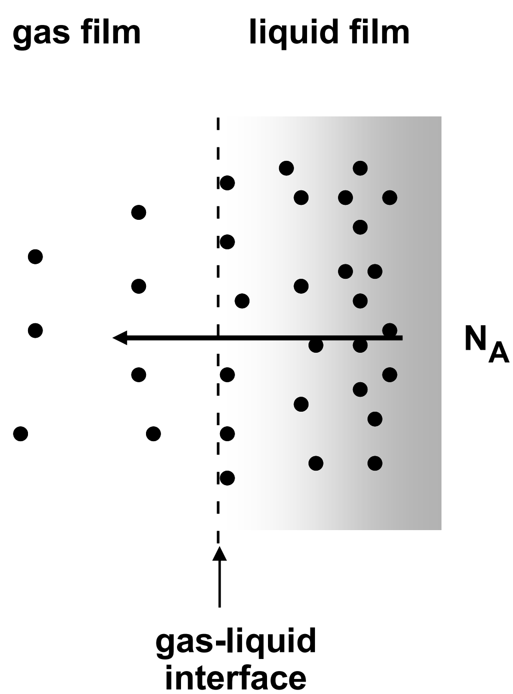


Introduction to Gas-Liquid Interphase Mass Transfer (cont.)

Gas Absorption
(Solute transferred from gas to liquid)



Liquid Stripping
(Solute transferred from liquid to gas)



• = solute molecule

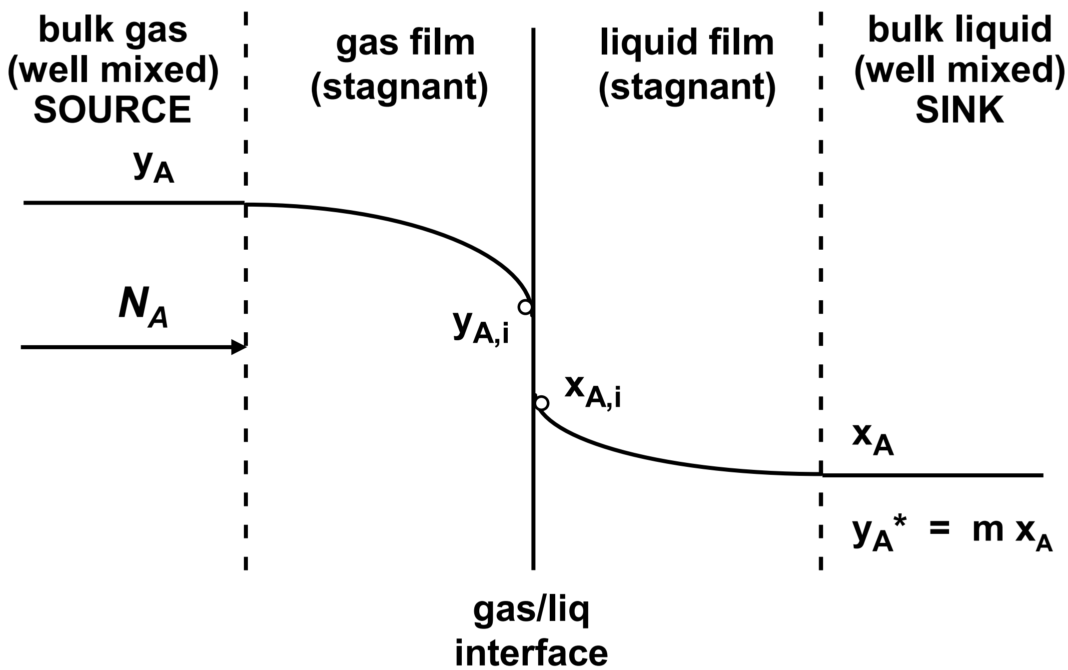
Gas Phase: **solute A + carrier gas**

Liquid Phase: **solute A + solvent**

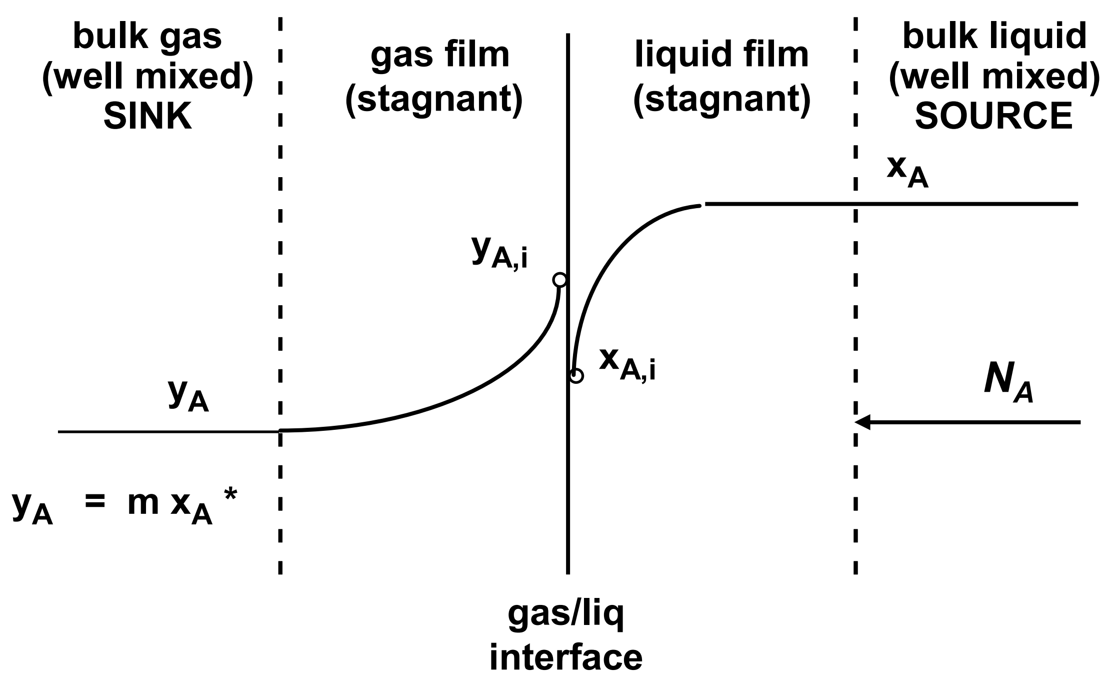
The carrier gas and solvent are considered immiscible in one another

Introduction to Gas-Liquid Interphase Mass Transfer (cont.)

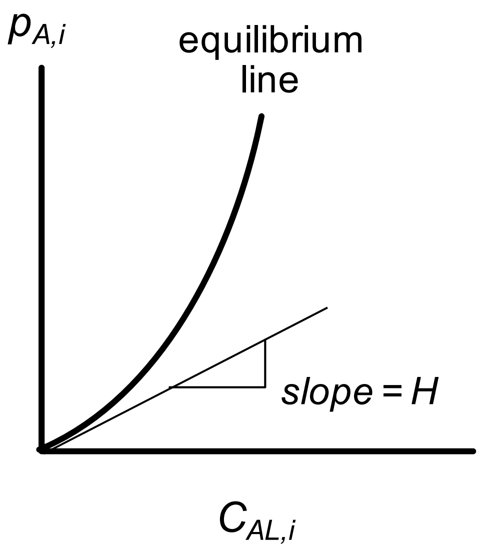
Gas Absorption



Liquid Stripping



29.1 Equilibrium distribution curve and Henry's Law



P_A (or p_A) vs. C_{AL}

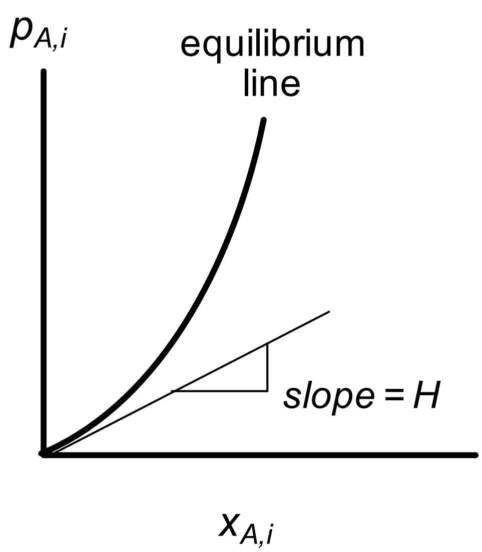
At interface:

$$P_{A,i} = H\, C_{AL,i}$$

At equilibrium
($P_A = P_{A,i}$, $C_{AL} = C_{AL,i}$):

$$P_A = H\, C_{AL}$$

***H** units: e.g.* atm / (kgmole/m^3)



P_A (or p_A) vs. x_A

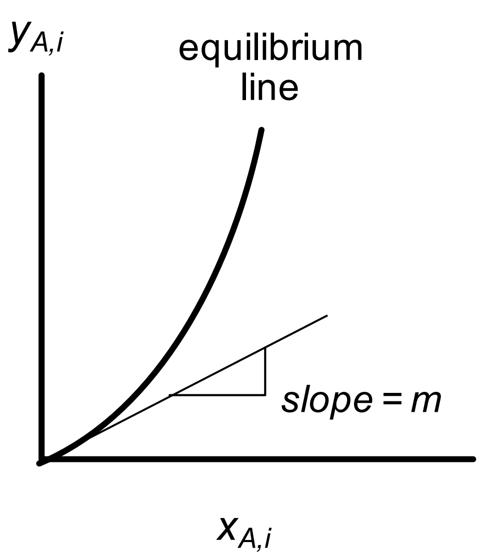
At interface:

$$P_{A,i} = H\, x_{A,i}$$

At equilibrium
($P_A = P_{A,i}$, $C_{AL} = C_{AL,I}$):

$$P_A = H\, x_A$$

***H** units: e.g.* atm / mol fraction (atm)



y_A vs. x_A

At interface:

$$y_{A,i} = m\, x_{A,i}$$

At equilibrium
($P_A = P_{A,i}$, $x_A = x_{A,i}$):

$$y_A = m\, x_A$$

***m** units: dimensionless*

29.1 Equilibrium distribution curve and Henry's Law (cont.)

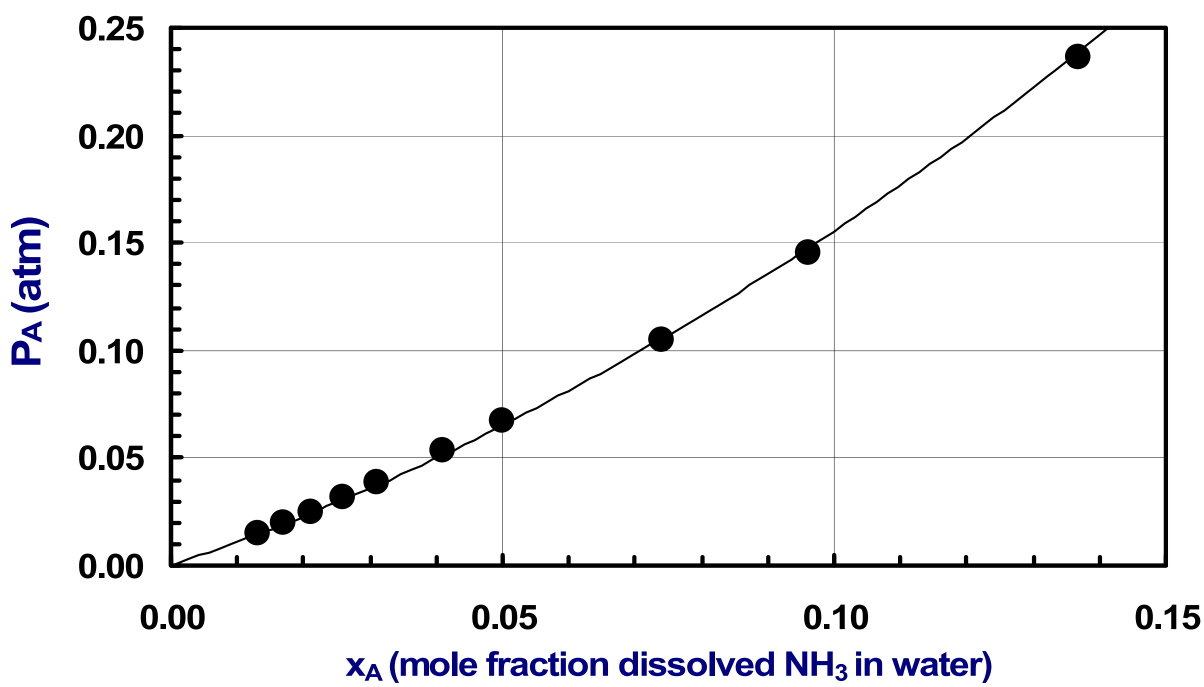
Example:

Ammonia (NH_3, solute A) – Water (H_2O, solvent) – Air (Carrier Gas) System

Gas Phase: NH_3 vapor + Air

Liquid Phase: NH_3 dissolved in Water

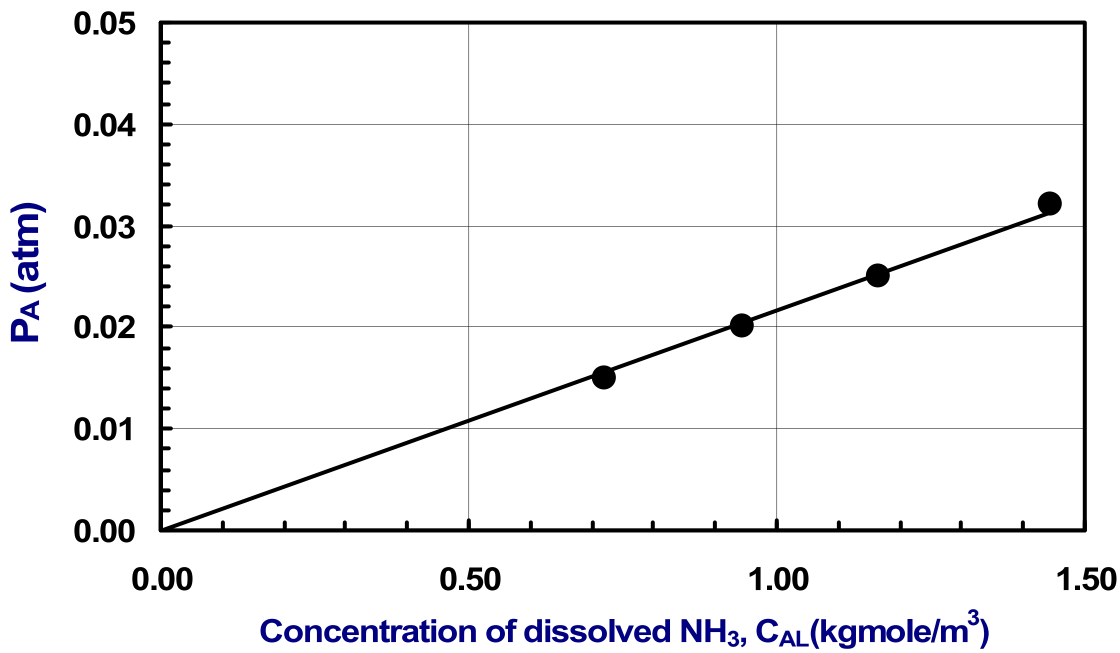
Equilibrium Distribution Curve (P_A-x_A)



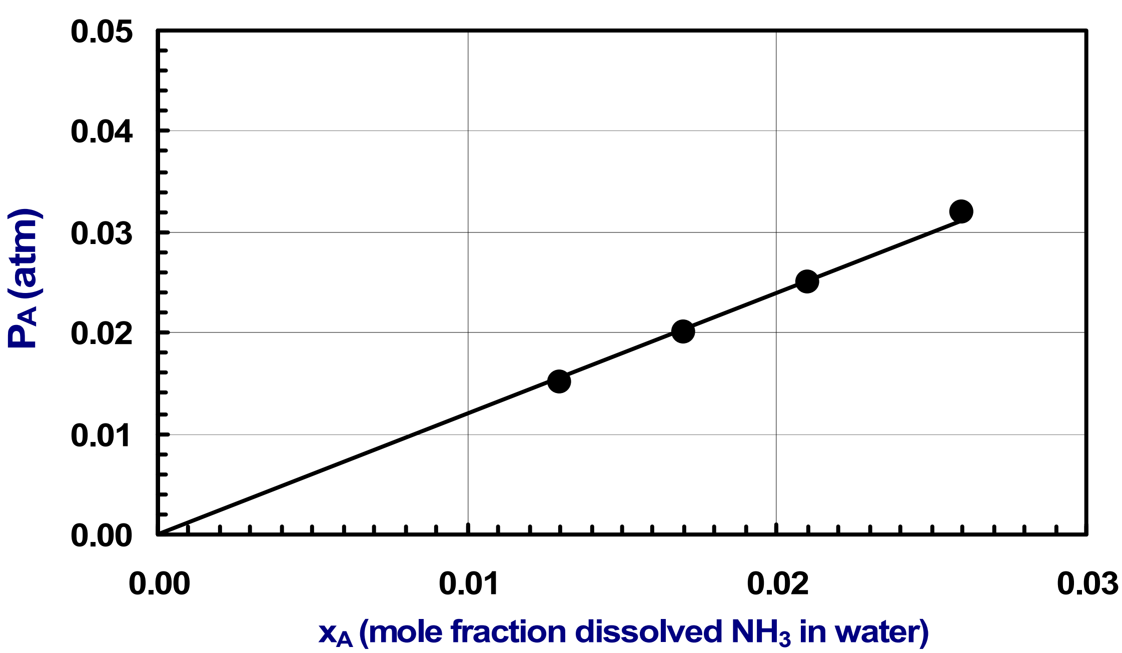
Gas Phase: **NH_3 vapor + Air**

Liquid Phase: **NH_3 dissolved in Water**

Equilibrium Distribution Curve (P_A-C_{AL})
Low Concentration Range (Linear Region, Henry's Law)



Equilibrium Distribution Curve (P_A-x_A)
Low Concentration Range (Linear Region, Henry's Law)



29.1 Equilibrium Distribution Curve and Henry's Law (continued)

- Solute A distributed between gas phases and dissolved phase in inert solvent
- Carrier gas and solvent are immiscible
- Fixed total system pressure (P) and temperature (T)

Units of Equilibrium Distribution Coefficient

Relationship	Gas Phase Units	Liquid Phase Units	Distribution Coefficient	Units of Equilibrium Distribution Coefficient
$P_{A,i} = H\, C_{AL,i}$	atm	kgmole/m^3	$H = m\, P / C_L$	atm / (kgmole/m^3)
$P_{A,i} = H\, x_{A,i}$	atm	mol. fract.	$H = m\, P$	atm
$y_{A,i} = m\, x_{A,i}$	mol. fract.	mol. fract.	m	dimensionless

Gas ***Liquid***

$\boldsymbol{P_A = y_A P}$ $\boldsymbol{C_{AL} = x_A C_L}$

$\boldsymbol{P_{A,i} = y_{A,i} P}$ $\boldsymbol{C_{AL,i} = x_{A,i} C_L}$

$\boldsymbol{P}$ = total system pressure in gas phase, atm

$\boldsymbol{C_L}$ = total molar concentration of liquid phase, kgmol/m^3 (solute-species ***A***, plus solvent ***B***)

Note for dilute solutions

$$C_L \cong \frac{\rho_B}{M_B}$$

where

$\boldsymbol{\rho_B}$ = mass density of solvent, kg/m^3

$\boldsymbol{M_B}$ = molecular weight of solvent, kg/kgmole

Typical Values for H as defined by $P_{1,i} = H x_{1,i}$
(for comparative purposes only, always look up and cite reference)

Sparingly Soluble (H > 100 atm)	Soluble (H < 1.0 atm)
Dissolved O_2 gas in water 293 K $H = 4.3 \times 10^4$ atm Dissolved CO_2 gas in water 293 K $H = 1.6 \times 10^3$ atm Dissolved trichloroethylene vapor in water 293 K, H = 556 atm	Very highly soluble Ethanol vapor in water at 293 K, H = 0.30 atm NH_3 vapor in water at 293 K, H = 0.9 atm Intermediate solubility SO_2 in water at 293 K, H = 46 atm

29.2 Two-Resistance Theory

29.2a Individual Film Mass Transfer Coefficients

Gas Film		
Driving Force	UMD Flux	Units of "k"
Partial Pressure (P_A)	$N_A = k_G(P_A - P_{A,i})$	kgmole A/(m^2-sec-atm)
Concentration (C_A)	$N_A = k_c(C_A - C_{A,i})$	kgmole A/(m^2-sec-(kgmole/m^3))
Mole Fraction (y_A)	$N_A = k_y(y_A - y_{A,i})$	kgmole A/(m^2-sec-Δy mole fract.)
Liquid Film		
Concentration (C_{AL})	$N_A = k_L(C_{AL,i} - C_{AL})$	kgmole A/(m^2-sec-(kgmole/m^3))
Mole Fraction (x_A)	$N_A = k_x(x_{A,i} - x_A)$	kgmole A/(m^2-sec-Δx mole fract.)

29.2b Overall Mass Transfer Coefficients

Two-Film Resistance Theory for Gas-Liquid Contacting

1. Solute is distributed between contacting gas and liquid phase
    - gas phase contains solute A + inert carrier gas
    - liquid phase contains solute A + inert solvent
    - carrier gas and solvent are *immiscible*

2. No accumulation of solute A within the gas or liquid film (nominal steady state)

3. The rate of mass transfer for a given solute is dependent on the concentration gradient of solute "A" which is localized in the film for each phase. At steady state, the flux through the gas film and the liquid film are equal ($N_{A,G} = N_{A,L} = N_A$).

4. There is no mass transfer resistance *at the gas-liquid interface*: equilibrium distribution of solute A between gas and liquid exists only at the interface

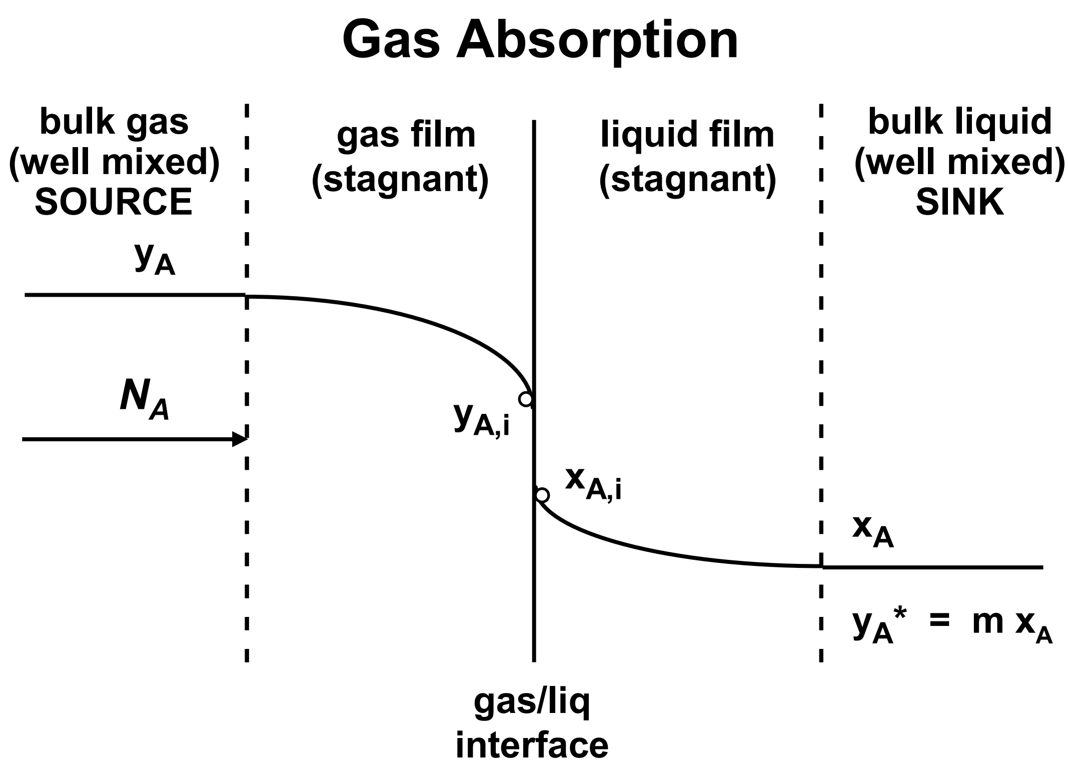
5. Unimolecular mass transfer process:
   diffusion of solute A through nondiffusing B, where B is the carrier gas for the gas phase, or B is the solvent for the liquid phase.

29.2b Overall Mass Transfer Coefficients (cont.)

In convective gas-liquid interphase mass transfer, the thickness of the gas and liquid films is very small. Therefore, the "accumulation" of transferring solute A *within the film* (not the whole process) will be small, and so

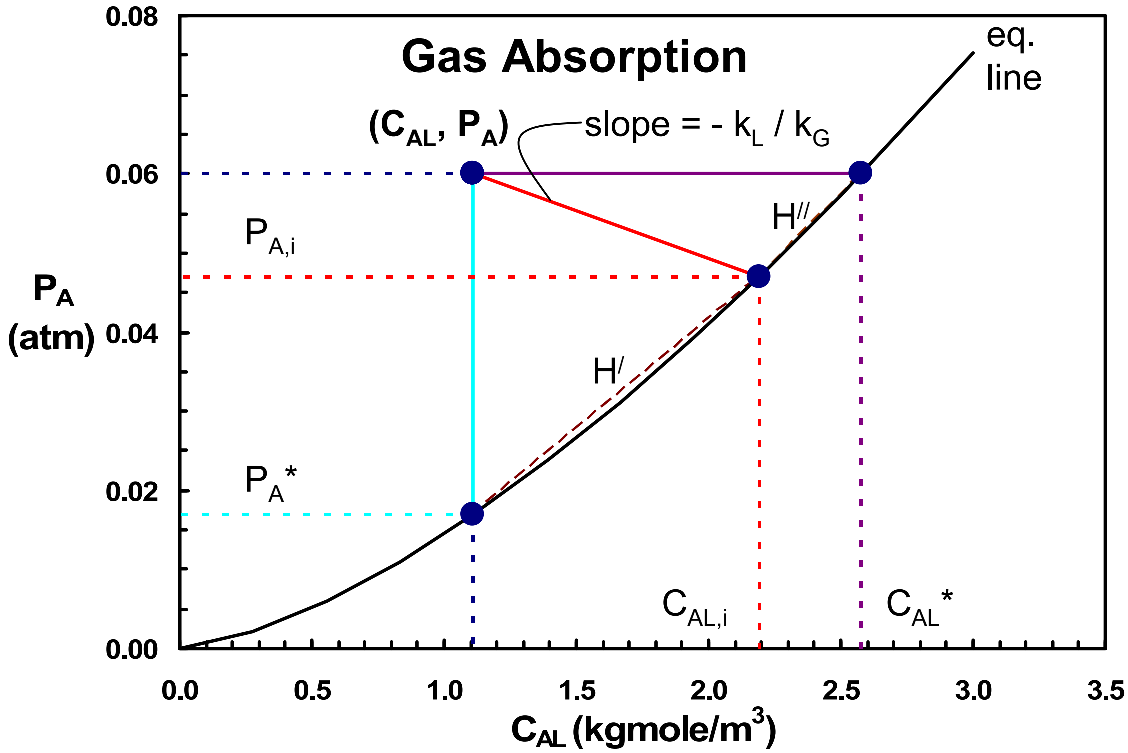
$$N_A = N_{A,gas\ film} = N_{A,liquid\ film}$$

Big picture: develop an "overall mass transfer coefficient" to calculate N_A based on only bulk gas and bulk liquid "solute A" compositions

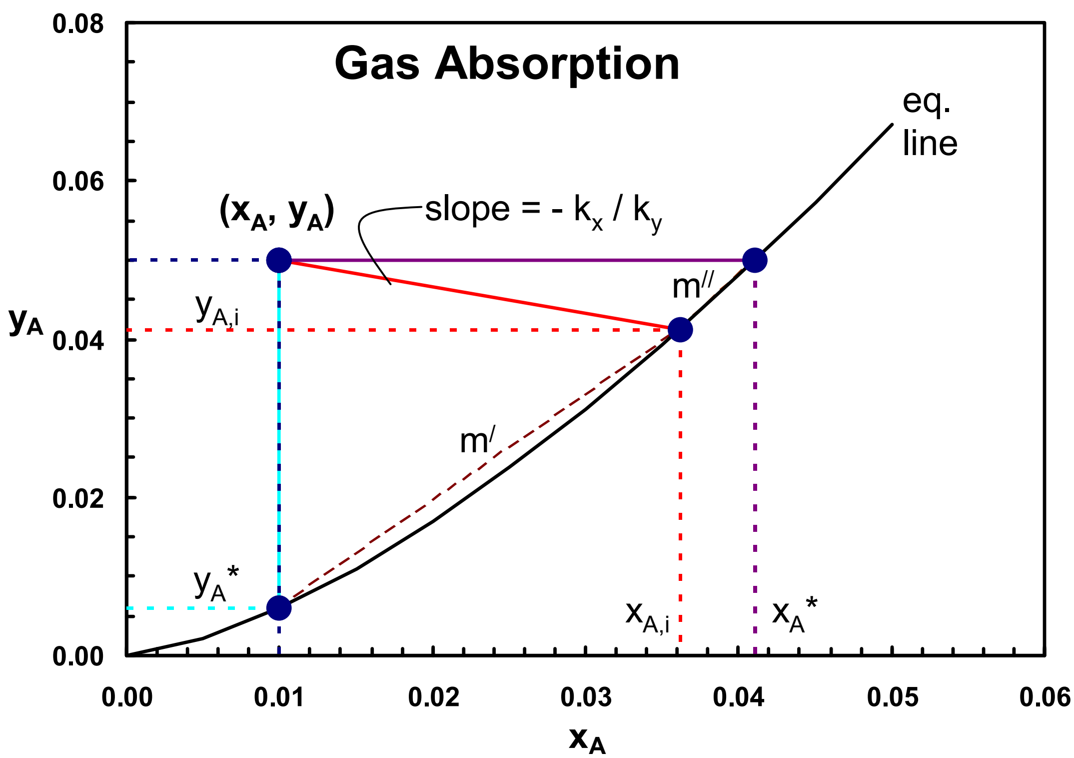


- Refer to P_A-C_{AL} and y_A-x_A diagrams
- The bulk gas composition of solute A (e.g. P_A or y_A) and bulk liquid composition of solute A (e.g. C_{AL} or x_A) are represented as a single point called the "operating point"… the operating point is not at equilibrium
  - Gas absorption: "operating point" is *above* the equilibrium line
  - Liquid stripping: "operating point" is *below* the equilibrium line

P_A - C_{AL}


Gas Absorption
eq. line
(C_{AL}, P_A)
slope = - k_L / k_G
$H^{//}$
$P_{A,i}$
P_A (atm)
$H^{/}$
P_A^*
$C_{AL,i}$
C_{AL}^*
0.00
0.02
0.04
0.06
0.08
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
C_{AL} (kgmole/m^3)

y_A - x_A


Gas Absorption
eq. line
(x_A, y_A)
slope = - k_x / k_y
$m^{//}$
$y_{A,i}$
y_A
$m^{/}$
y_A^*
$x_{A,i}$
x_A^*
0.00
0.02
0.04
0.06
0.08
0.00
0.01
0.02
0.03
0.04
0.05
0.06
x_A

29.2b Overall Mass Transfer Coefficients (cont.)

Gas Absorption – Overall Mass Transfer Coefficients

Gas Film

$$N_A = k_G\left(P_A - P_{A,i}\right)$$

$$N_A = k_y(y_A - y_{A,i})$$

Liquid Film

$$N_A = k_L\left(C_{AL,i} - C_{AL}\right)$$

$$N_A = k_x(x_{A,i} - x_A)$$

Equate Film Fluxes

$$-\frac{k_L}{k_G} = \frac{p_A - p_{A,i}}{C_{AL} - C_{AL,i}} \qquad \text{or} \qquad -\frac{k_x}{k_y} = \frac{y_A - y_{A,i}}{x_A - x_{A,i}}$$

We can graphically locate interphase compositions (e.g. $\boldsymbol{P_{A,i}}$-$\boldsymbol{C_{AL,i}}$ and $\boldsymbol{y_{A,i}}$-$\boldsymbol{x_{A,i}}$) using the point-slope formula above, with locus of intersection at the equilibrium line

Note: bulk compositions P_A-$\boldsymbol{C_{AL}}$ or $\boldsymbol{y_A}$-$\boldsymbol{x_A}$ are easily determined

interphase compositions $P_{A\,i}$-$\boldsymbol{C_{AL,i}}$ or $\boldsymbol{y_{A,i}}$-$\boldsymbol{x_{A,i}}$ are not easily determined

Rewrite driving force for $\boldsymbol{N_A}$ based on bulk compositions

Overall Gas Phase

$$N_A = K_G\left(P_A - P_A^*\right)$$

$$N_A = K_y(y_A - y_A^*)$$

Overall Liquid Phase

$$N_A = K_L\left(C_{AL}^* - C_{AL}\right)$$

$$N_A = K_x(x_A^* - x_A)$$

$\boldsymbol{P_A}$***** = partial pressure of solute A in gas which "would be" in equilibrium with bulk liquid composition $\boldsymbol{C_{AL}}$

$\boldsymbol{y_A}$***** = mole fraction of solute A in gas which "would be" in equilibrium with bulk liquid mole fraction $\boldsymbol{x_A}$

$\boldsymbol{C_{AL}}$***** = molar concentration of solute A in liquid which "would be" in equilibrium with bulk gas partial pressure $\boldsymbol{P_A}$

$\boldsymbol{x_A}$***** = mole fraction of solute A in liquid which "would be" in equilibrium with bulk gas mole fraction $\boldsymbol{y_A}$

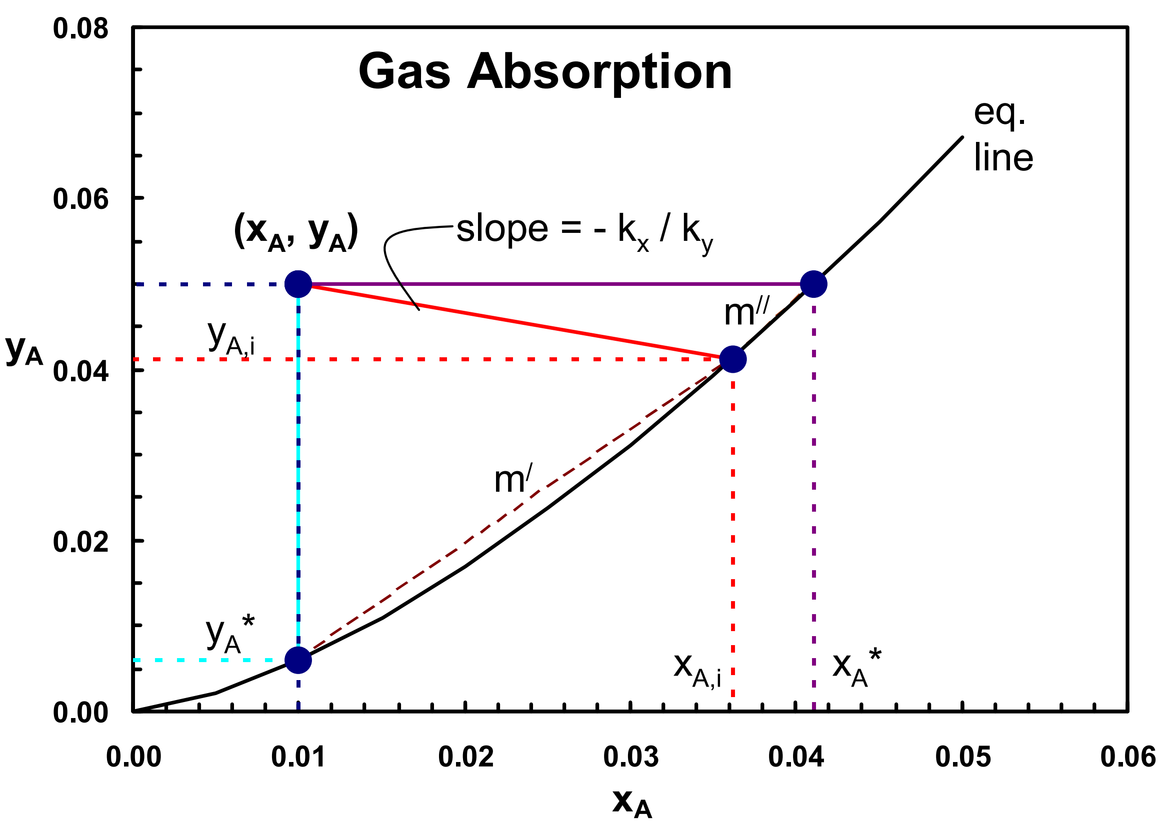
Refer to $\boldsymbol{P_A}$-$\boldsymbol{C_{AL}}$ **or** $\boldsymbol{y_A}$-$\boldsymbol{x_A}$ diagrams

Approximate: $y_A^* = m' x_A$ and $y_{A,i} = m' x_{Ai}$

$p_A^* = H' C_{AL}$ and $p_{A,i} = H' C_{AL,i}$

H' is a linear approximation of the equilibrium curve from C_{AL} to $C_{AL,i}$

m' is a linear approximation of the equilibrium curve from x_A to $x_{A,i}$



Therefore (finishing up with mole fraction coordinates as the example)

$$y_A - y_A^* = (y_A - y_{A,i}) + (y_{A,i} - y_A^*) = (y_A - y_{A,i}) + m'(x_{A,i} - x_A) \qquad (1)$$

Recall

$$N_A = K_y(y_A - y_A^*) \quad \text{or} \quad \frac{N_A}{K_y} = (y_A - y_A^*) \qquad (2)$$

$$N_A = k_y(y_A - y_{A,i}) \quad \text{or} \quad \frac{N_A}{k_y} = (y_A - y_{A,i}) \qquad (3)$$

$$N_A = k_x(x_{A,i} - x_A) \quad \text{or} \quad \frac{N_A}{k_x} = (x_{A,i} - x_A) \qquad (4)$$

Combine (2), (3) and (4) with (1)

$$\therefore \frac{N_A}{K_y} = \frac{N_A}{k_y} + m'\frac{N_A}{k_x}$$

Finally, the ***Overall Gas Phase Mass Transfer Coefficients*** based on an overall gas phase driving force ($y_A - y_A^*$) or ($p_A - p_A^*$)

Nonlinear equilibrium	Linear equilibrium ($m'=m$, $H' = H$)	Driving force
$\frac{1}{K_y} = \frac{1}{k_y} + \frac{m'}{k_x}$	$\frac{1}{K_y} = \frac{1}{k_y} + \frac{m}{k_x}$	($y_A - y_A^*$)
$\frac{1}{K_G} = \frac{1}{k_G} + \frac{H'}{k_L}$	$\frac{1}{K_G} = \frac{1}{k_G} + \frac{H}{k_L}$	($p_A - p_A^*$)

By a similar analysis, the ***Overall Liquid Phase Mass Transfer Coefficients*** based on an overall liquid phase driving force ($x_A^* - x_A$) or (C_{AL}^* - C_{AL})

Nonlinear equilibrium	Linear equilibrium ($m''=m$, $H'' = H$)	Driving force
$\frac{1}{K_x} = \frac{1}{k_x} + \frac{1}{m'' k_y}$	$\frac{1}{K_x} = \frac{1}{k_x} + \frac{1}{m\, k_y}$	($x_A^* - x_A$)
$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{H'' k_G}$	$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{H\, k_G}$	(C_{AL}^* - C_{AL})

Overall Mass Transfer Coefficients – Film Controlling Resistances

Define relative gas phase resistance

$$\frac{1/k_G}{1/K_G} = \frac{1/k_y}{1/K_y} = \frac{\text{resistance to solute A mass transfer in gas film}}{\text{total resistance based on overall gas phase driving force}}$$

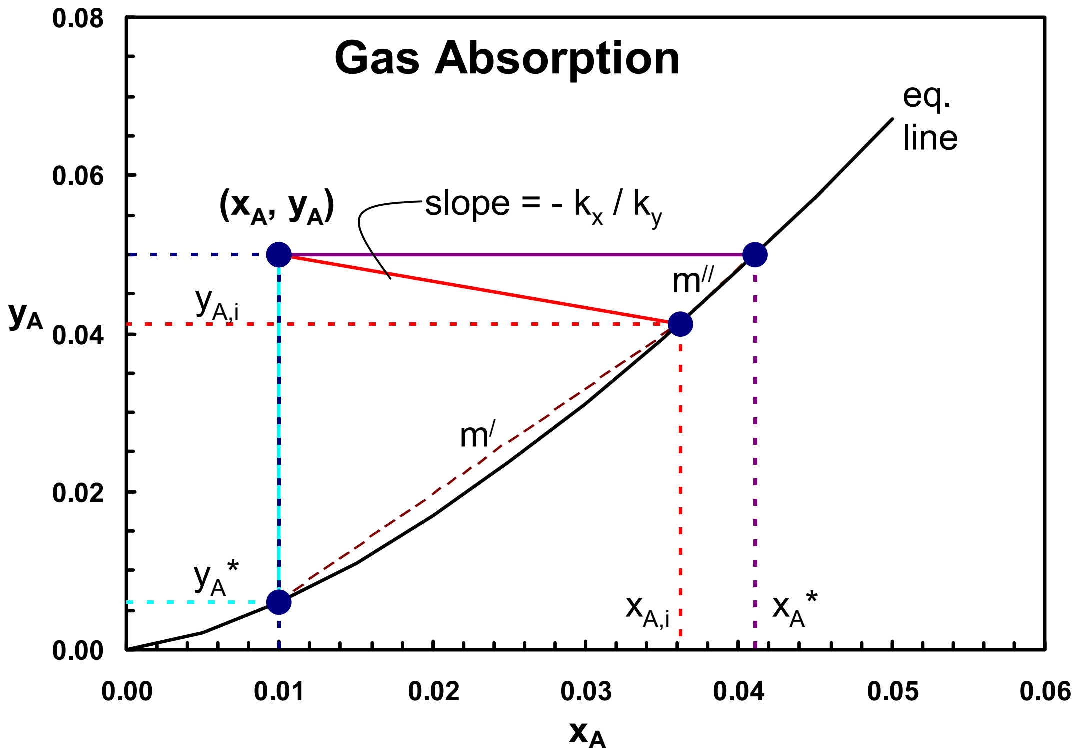
Define relative liquid phase resistance

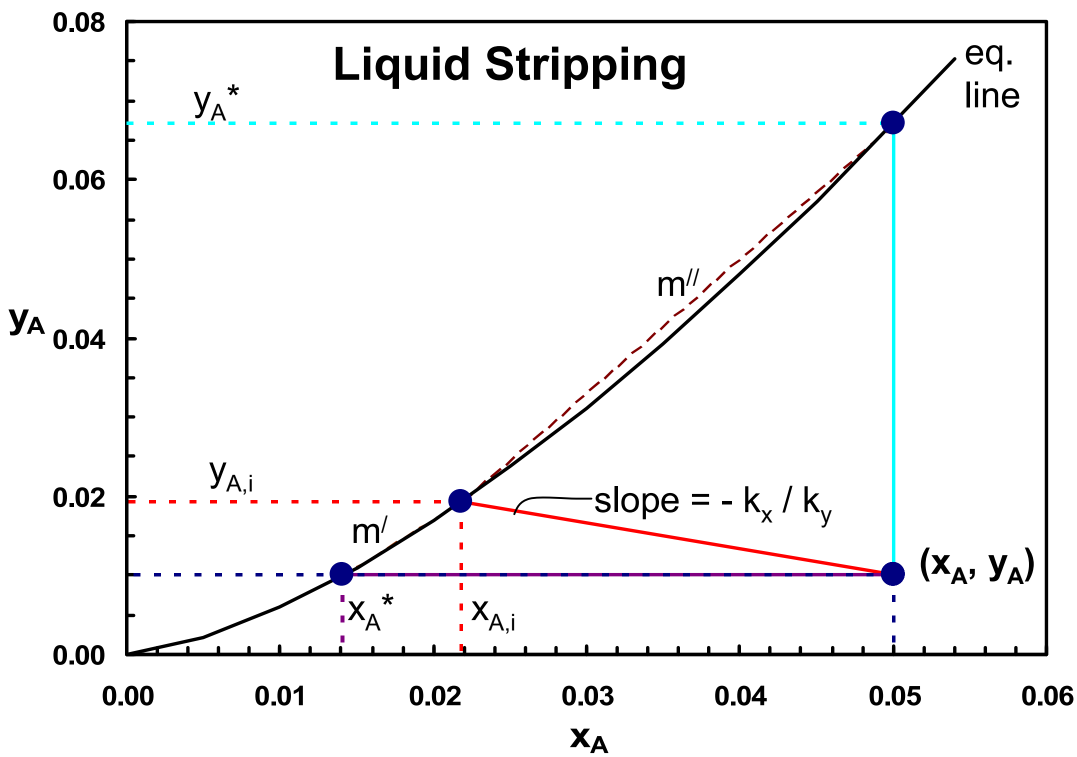
$$\frac{1/k_L}{1/K_L} = \frac{1/k_x}{1/K_x} = \frac{\text{resistance to solute A mass transfer in liquid film}}{\text{total resistance based on overall liquid phase driving force}}$$

note $\frac{1/k_y}{1/K_y} = 1 - \frac{1/k_x}{1/K_x}$ only if equilibrium line is linear!

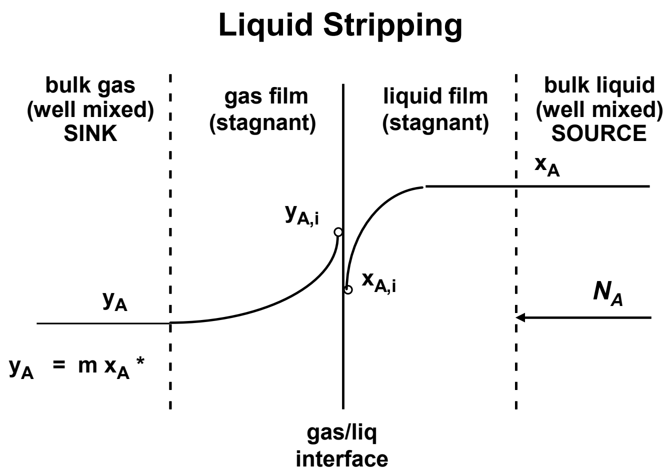
Gas film controlling resistance	*Liquid film controlling resistance*
m is very small (highly soluble A)	*m* is very large (sparingly soluble A)
and/or $k_x >> k_y$	and/or $k_y >> k_x$
$K_y \rightarrow k_y$ or $K_G \rightarrow k_G$	$K_x \rightarrow k_x$ or $K_L \rightarrow k_L$
$y_{Ai} \rightarrow y_A{*}$ and $(x_{Ai} - x_A) \rightarrow 0$	$x_{Ai} \rightarrow x_A{*}$ and $(y_A - y_{Ai}) \rightarrow 0$

Gas Absorption vs. Liquid Stripping





Liquid Stripping – Overall Mass Transfer Coefficients



Overall *Gas Phase* Mass Transfer Coefficients based on an overall gas phase driving force (y_A*- y_A) or (p_A*- p_A)

Nonlinear equilibrium	Linear equilibrium ($m''=m$, $H''=H$)	Driving force
$\frac{1}{K_y}=\frac{1}{k_y}+\frac{m''}{k_x}$	$\frac{1}{K_y}=\frac{1}{k_y}+\frac{m}{k_x}$	(y_A*- y_A)
$\frac{1}{K_G}=\frac{1}{k_G}+\frac{H''}{k_L}$	$\frac{1}{K_G}=\frac{1}{k_G}+\frac{H}{k_L}$	(P_A*-P_A)

Overall *Liquid Phase* Mass Transfer Coefficients based on an overall liquid phase driving force (x_A- x_A^*) or (C_{AL}- C_{AL}*)

Nonlinear equilibrium	Linear equilibrium ($m'=m$, $H'=H$)	Driving force
$\frac{1}{K_x}=\frac{1}{k_x}+\frac{1}{m'k_y}$	$\frac{1}{K_x}=\frac{1}{k_x}+\frac{1}{m\,k_y}$	(x_A - x_A^*)
$\frac{1}{K_L}=\frac{1}{k_L}+\frac{1}{H'k_G}$	$\frac{1}{K_L}=\frac{1}{k_L}+\frac{1}{H\,k_G}$	(C_{AL} - C_{AL}*)

More Definitions

Nonlinear equilibrium line definitions of "m", the local equilibrium near operating point x_A, y_A

Gas Absorption

$$m' = \frac{y_{A,i} - y_A^*}{x_{A,i} - x_A}$$

$$m'' = \frac{y_A - y_{A,i}}{x_A^* - x_{A,i}}$$

Liquid Stripping

$$m' = \frac{y_{A,i} - y_A}{x_{A,i} - x_A^*}$$

$$m'' = \frac{y_A^* - y_{A,i}}{x_A - x_{A,i}}$$

Inter-Conversion of Film Mass Transfer Coefficients (Solute A)

Gas Film

$$k_G = \frac{k_c}{RT} \qquad k_G = \frac{k_y}{P} \qquad k_y = \frac{P}{RT} k_c$$

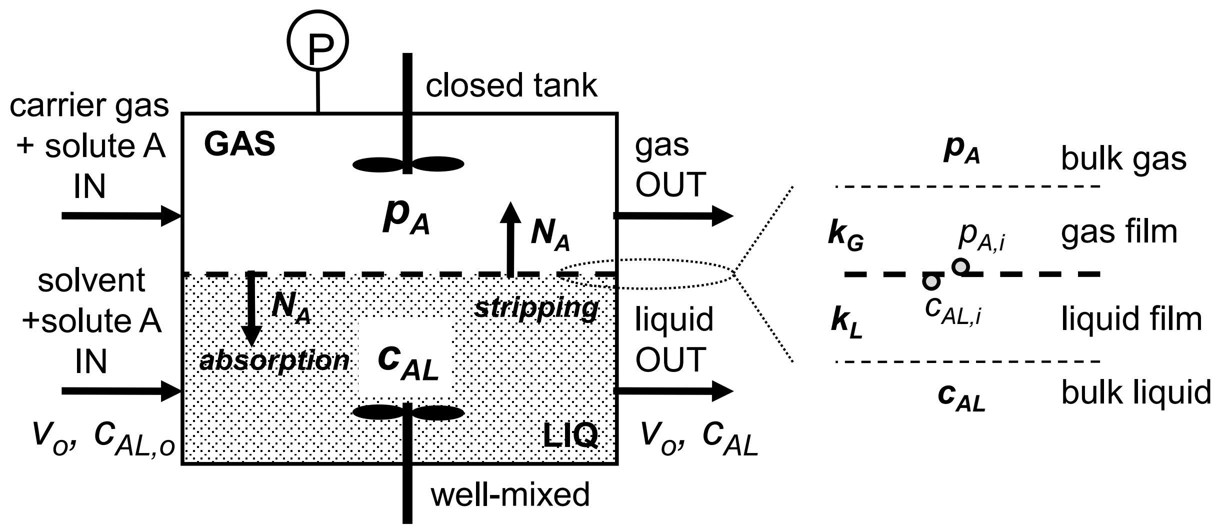
Liquid Film

$$k_x = C_L k_L \cong \frac{\rho_B}{M_B} k_L$$

29.2 cont.

Process examples of steady-state, well-mixed, gas-liquid mass transfer process across a defined interface

Closed Tank



Open Tank (or pond)