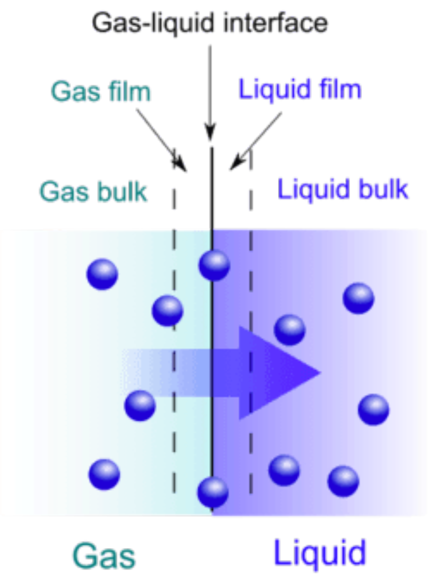
Lecture 9

Absorption processes… (continued)



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Intended learning outcome

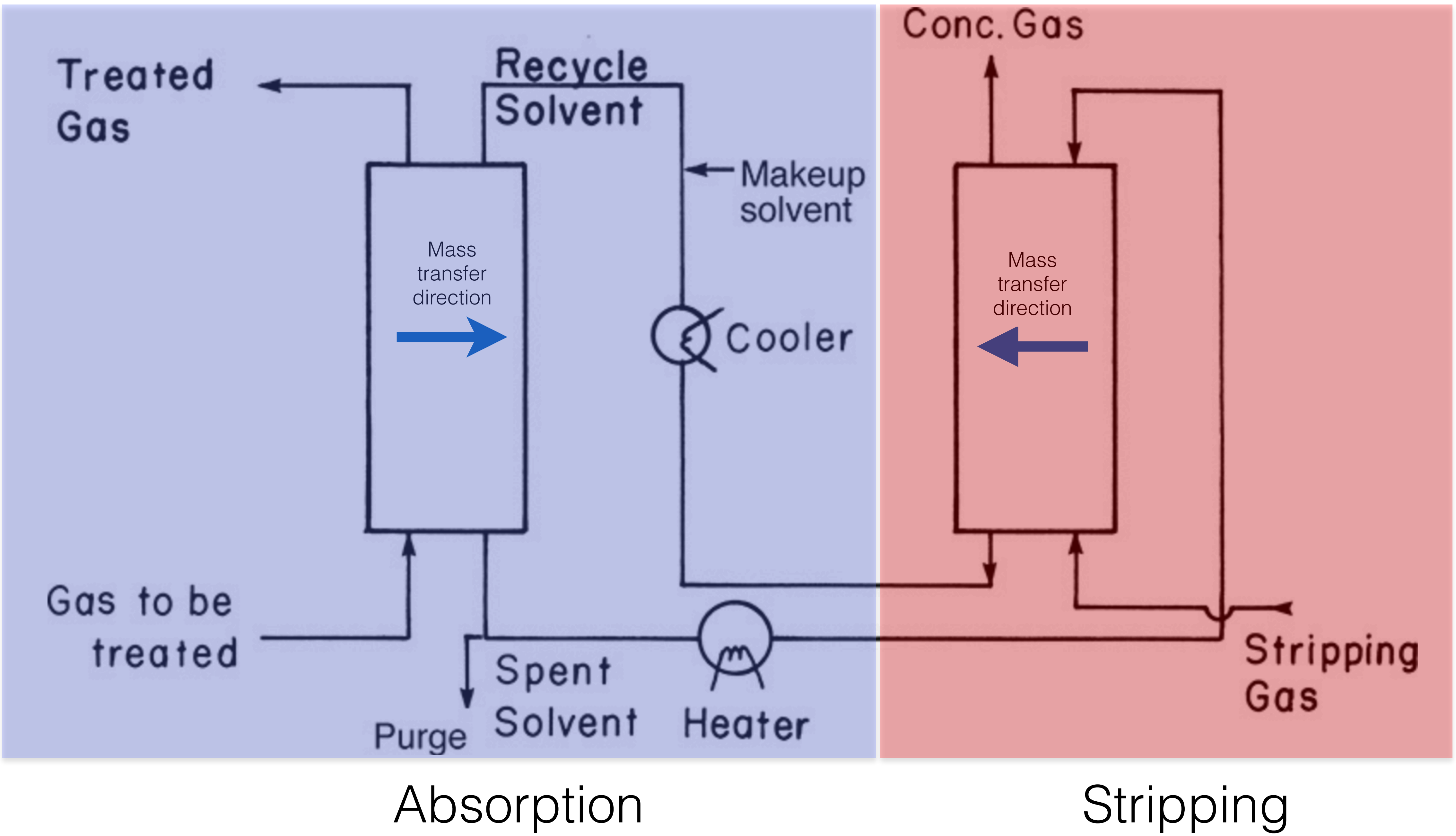
1. Revisit the configuration similarity and differences between the adsorption and stripping.
2. Apply graphical method to solve stripping problem (similar to absorption).
3. Basic concepts of mass transfer coefficient and diffusion.
4. Analyze the absorption problem when absorption is carried out in packed column.
5. Apply mass transfer coefficient to calculate height of the packed column, HTU and NTU for absorption/stripping in packed column.

Stripping is opposite of absorption

Example

CO_2 in N_2

H_2S in CH_4



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Dilute case: Stripping

Key assumptions:

1. Stripping gas is insoluble (stripping gas does not transfer to the absorbent phase).
2. Absorbent is nonvolatile (absorbent does not transfer to the stripping gas phase).

Implication:

1. Net flow rate of the liquid phase does not change.
2. Net flow rate of the gas phase does not change.
3. Usually, the operation is not isothermal, and the equilibrium line may not be linear.

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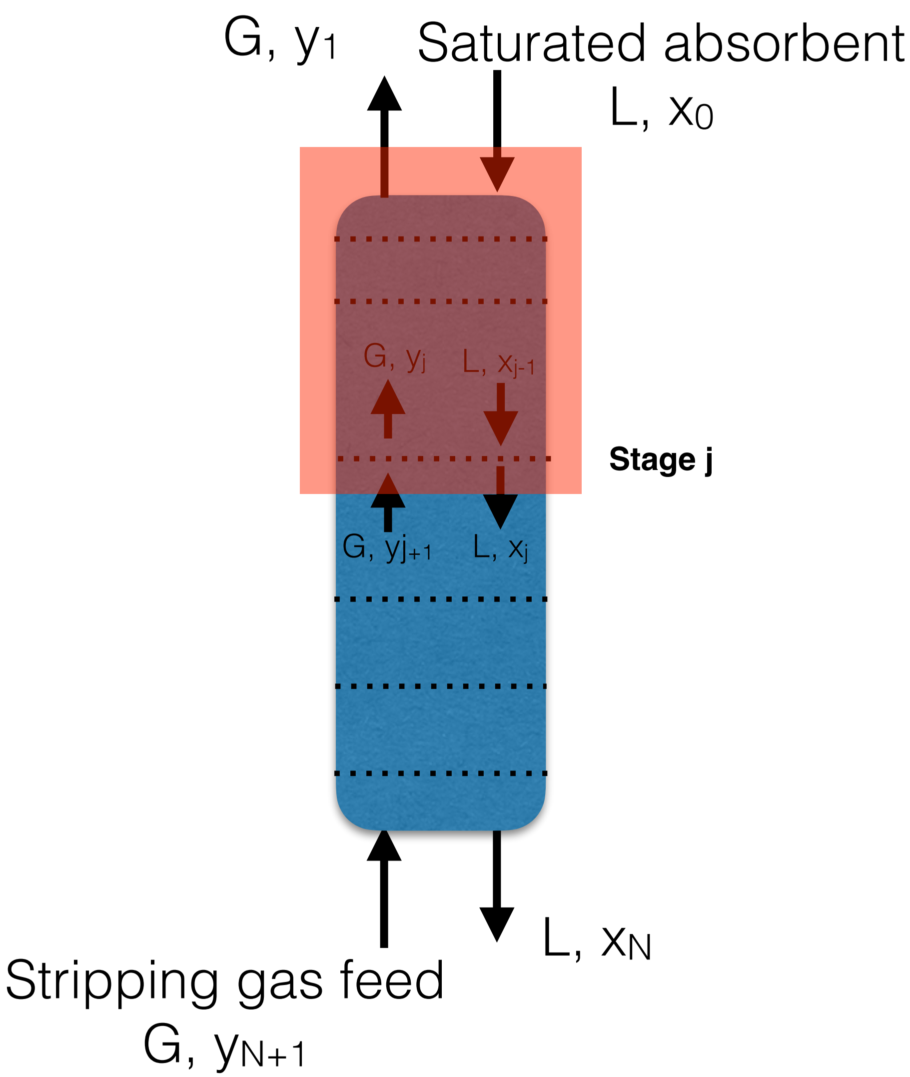
Stripping: mass balance for the dilute case



Balance around stage j

$$In = out$$

$$Gy_{j+1} + Lx_0 = Lx_j + Gy_1$$

$$y_{j+1} = \frac{L}{G}x_j + (y_1 - \frac{L}{G}x_0)$$

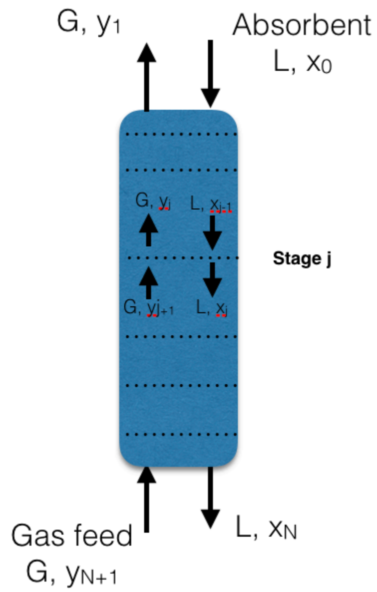
$$y_{N+1} = \frac{L}{G}x_N + (y_1 - \frac{L}{G}x_0)$$

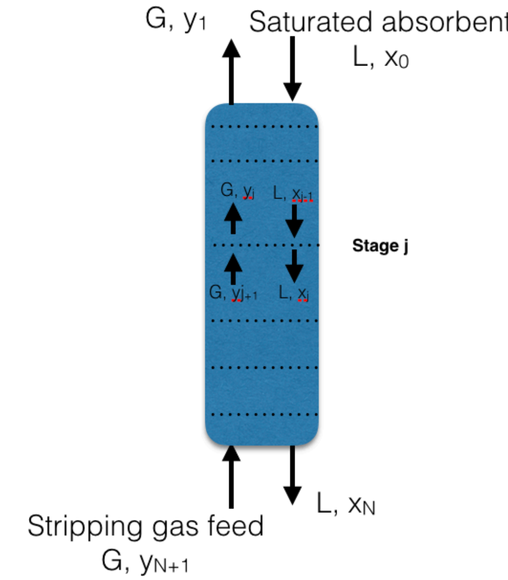
Operating line

$$y = \frac{L}{G}x + (y_1 - \frac{L}{G}x_0)$$

$$y = \frac{L}{G}x + (y_{N+1} - \frac{L}{G}x_N)$$

Absorption vs Stripping





	Absorption	**Stripping**
Operating line	$y=\frac{L}{G}x+(y_1-\frac{L}{G}x_0)$	$y=\frac{L}{G}x+(y_1-\frac{L}{G}x_0)$
	$y_1 < y_{N+1}, x_0 < x_N$	$y_1 > y_{N+1}, x_0 > x_N$
Phase description	Gas (y) Liquid, Absorbent (x) Mass transfer (↓)	Stripping gas (y) Liquid, Absorbent (x) Mass transfer (↑)
Equilibrium relationship	$m=\frac{H_x}{P}$	May or may not be linear

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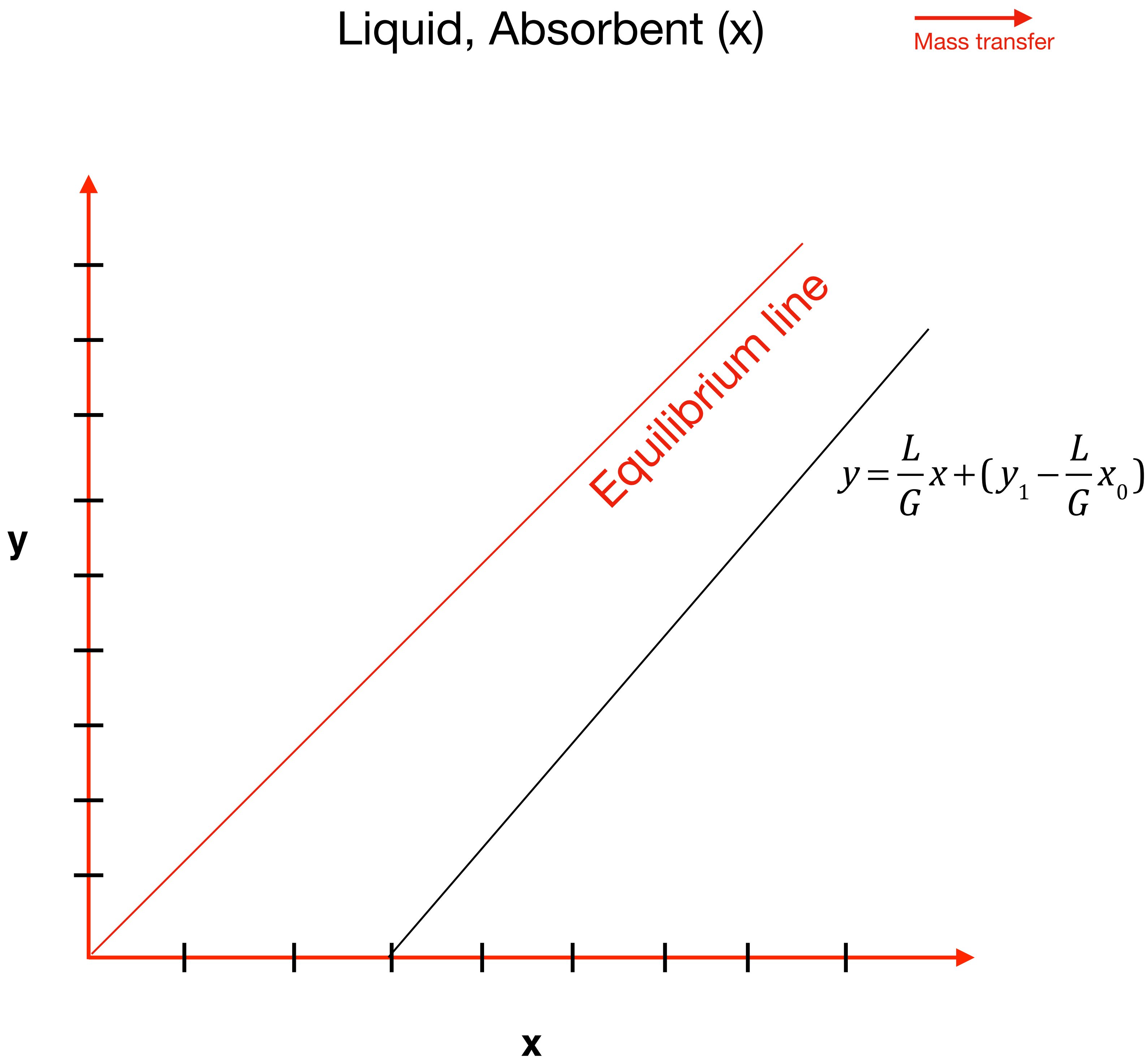
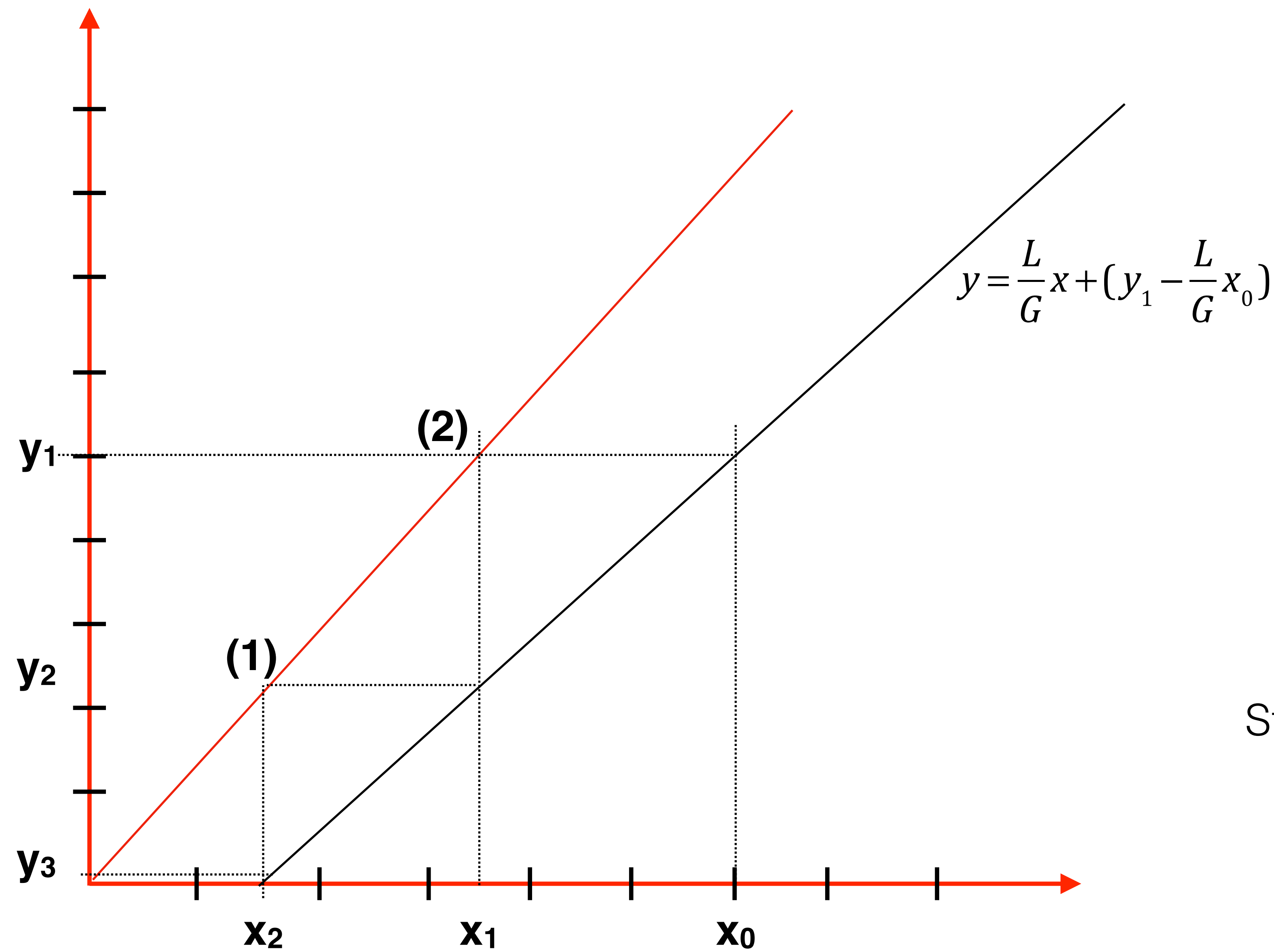
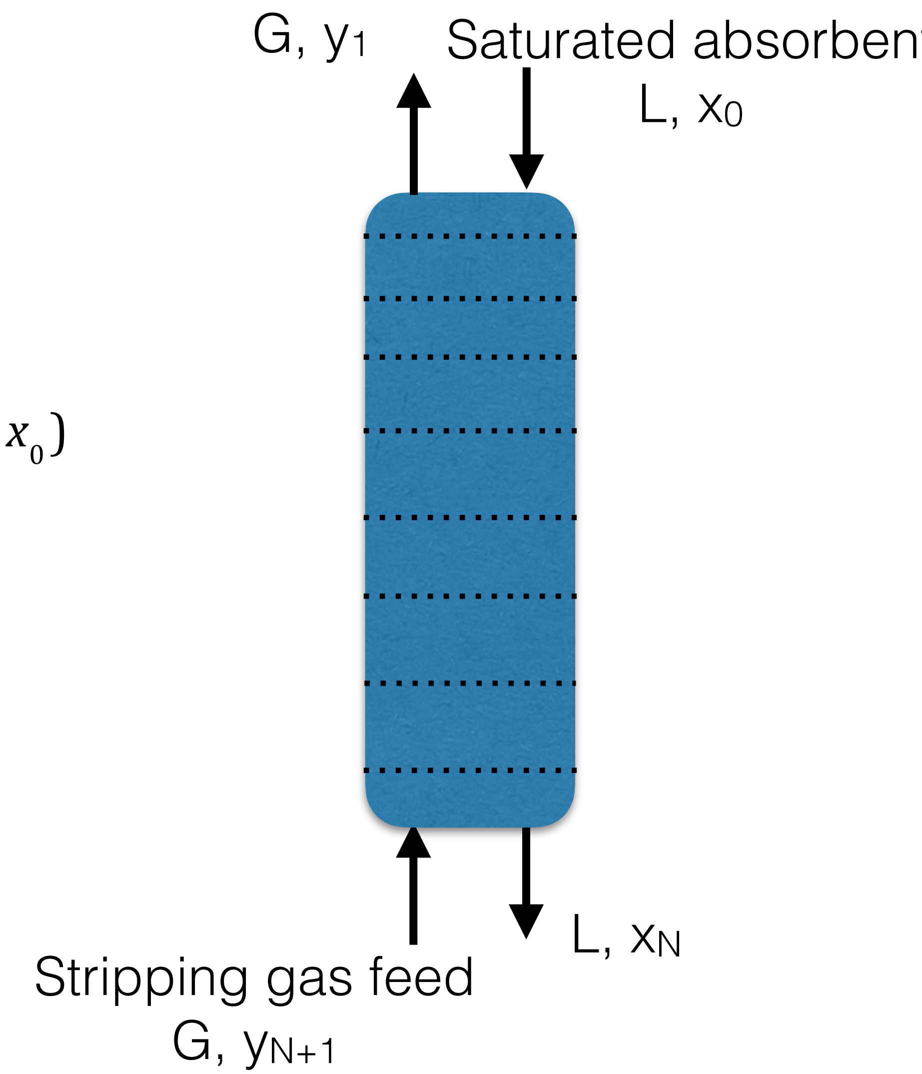
Stripping: Graphical method for number of stages

Liquid, Absorbent (x) → Stripping gas (y)



Calculation of number of stages



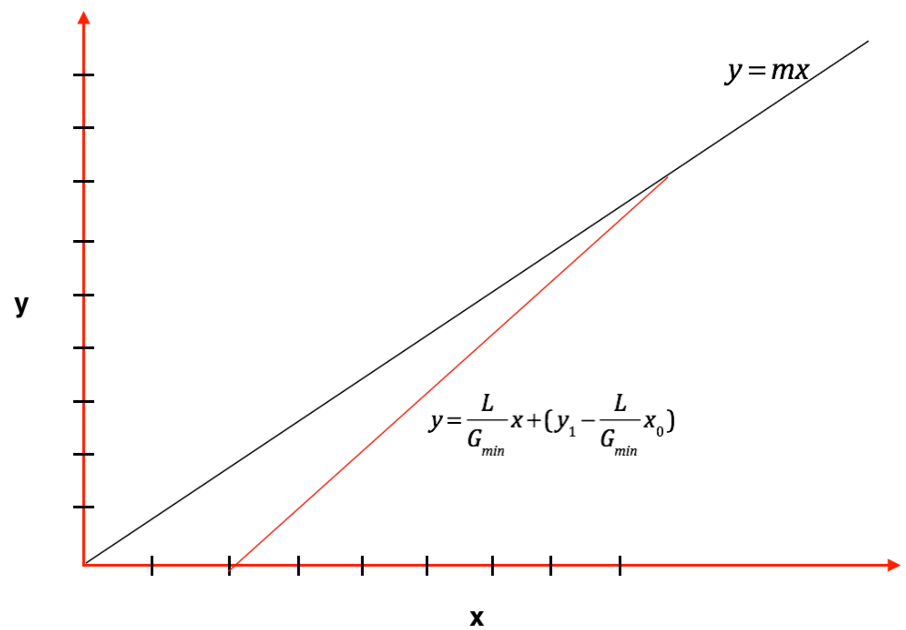


$y_1 > y_{N+1}$
$x_0 > x_N$

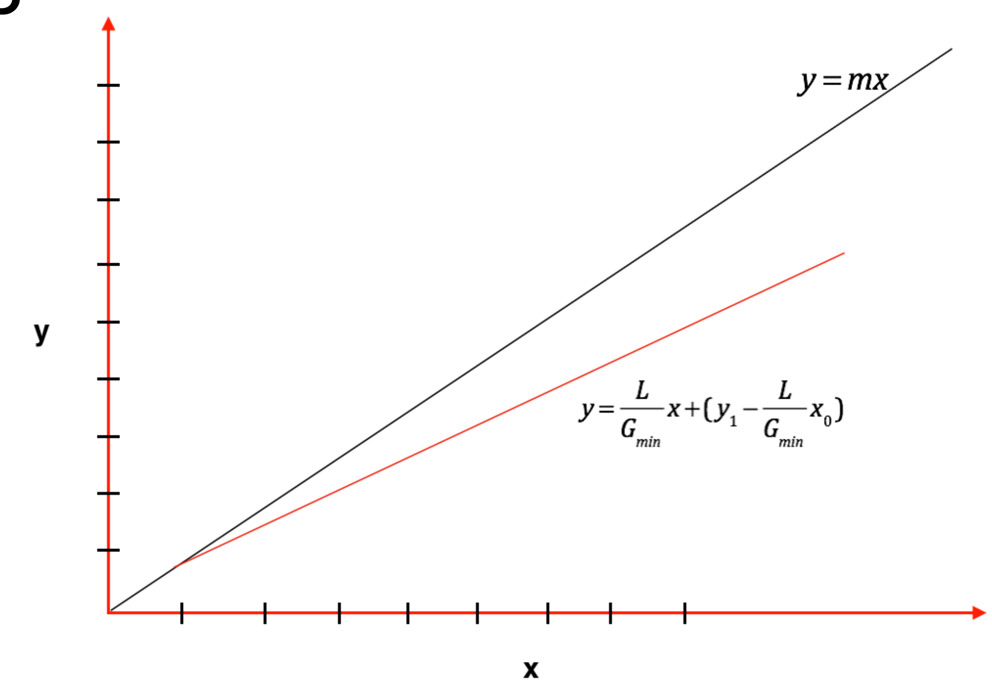
Minimum stripping gas flow rate

Which one is the correct representation??

A



B



C None of this

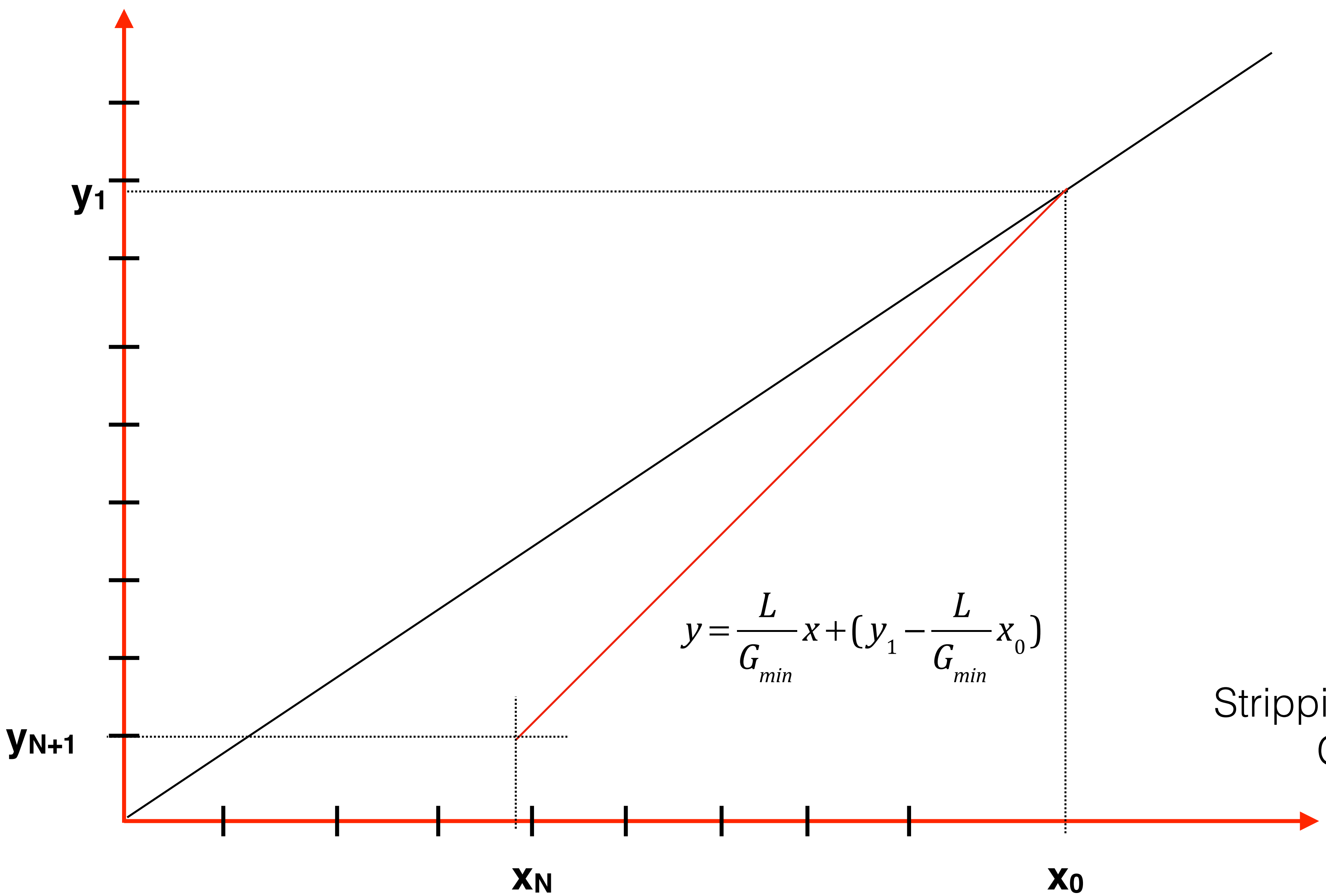
D Not enough info

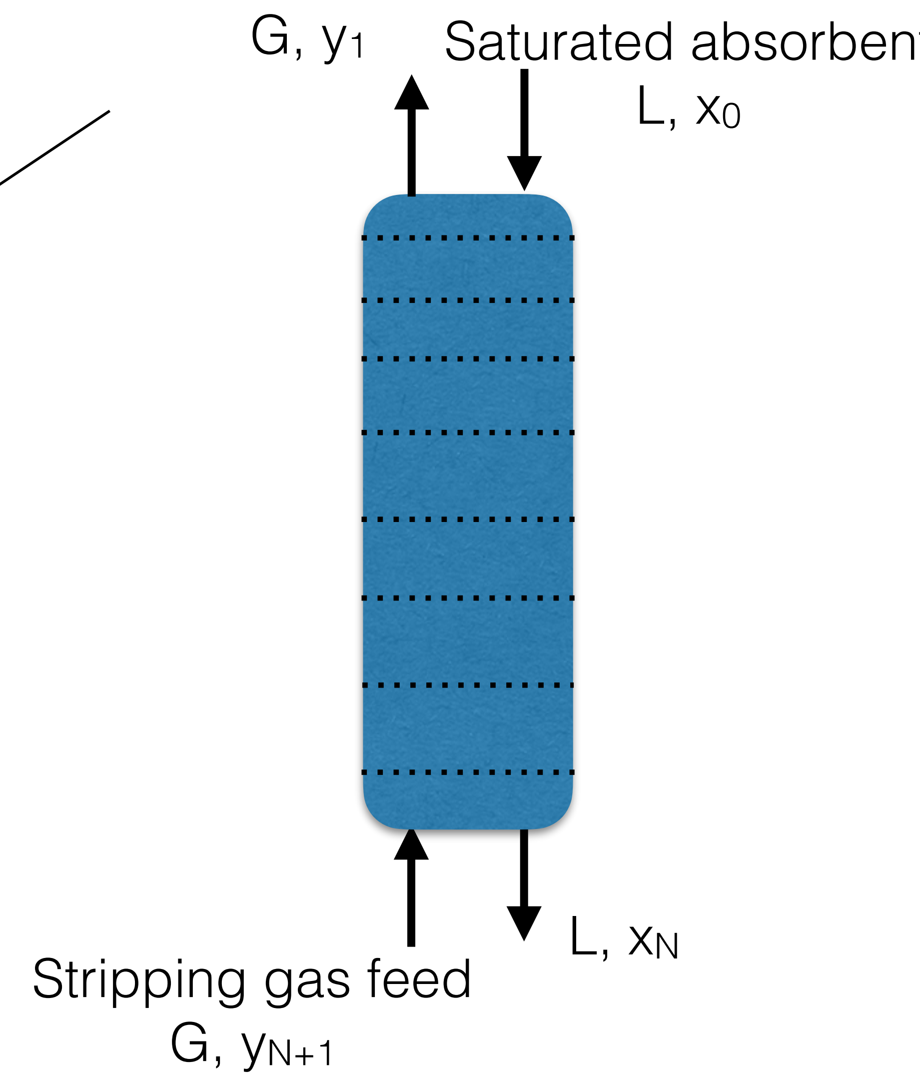
The slope of the operating line, L/G_{min}, is maximum

Minimum stripping gas flow rate

The slope of the operating line, L/G_{min}, is maximum

Number of stages is infinity





Quiz:

The operating lines for absorption (countercurrent), stripping (countercurrent), extraction (countercurrent) and distillation can be written as

$$y = Px + (y_1 - Px_0)$$

What does P stand for in the case of absorption, stripping, extraction and distillation

A. $\frac{L}{G}, \frac{G}{L}, \frac{R}{E}, \frac{L}{V}, \textit{ respectively}$

B. $\frac{L}{G}, \frac{L}{G}, \frac{R}{E}, \frac{L}{V}, \textit{ respectively}$

C. $1, 1, 1, \frac{V}{L}, \textit{ respectively}$

D. $\frac{L}{G}, \frac{L}{G}, \frac{E}{R}, \frac{V}{L}, \textit{ respectively}$

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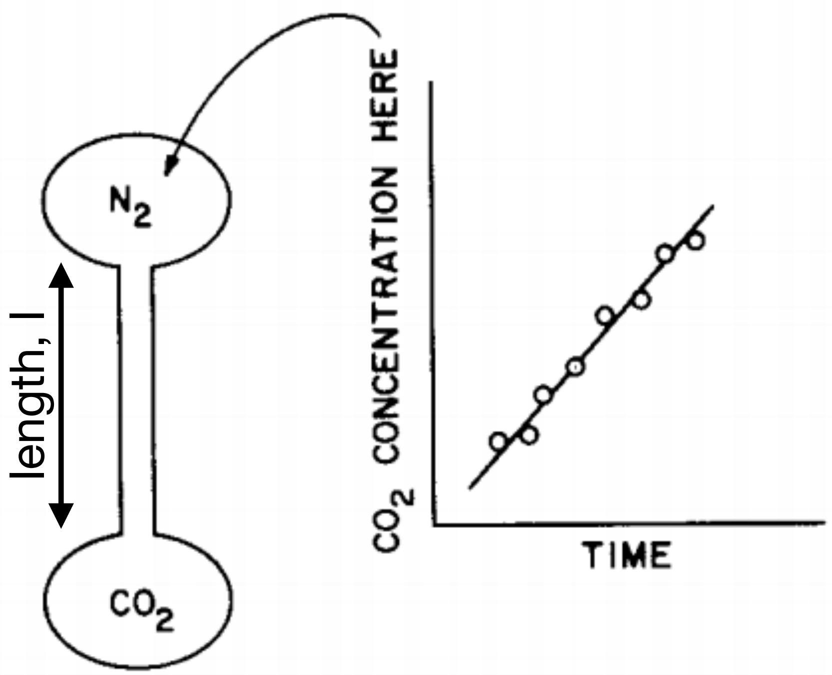
Diffusion vs. mass transfer coefficient



Rate of CO_2 increase $\propto$ ΔC of CO_2

Rate of CO_2 increase $= k\left(\Delta C_{CO_2}\right)$

Rate of CO_2 increase $\propto \frac{\left(\Delta C_{CO_2}\right)}{l}$

Rate of CO_2 increase $= D\frac{\left(\Delta C_{CO_2}\right)}{l}$

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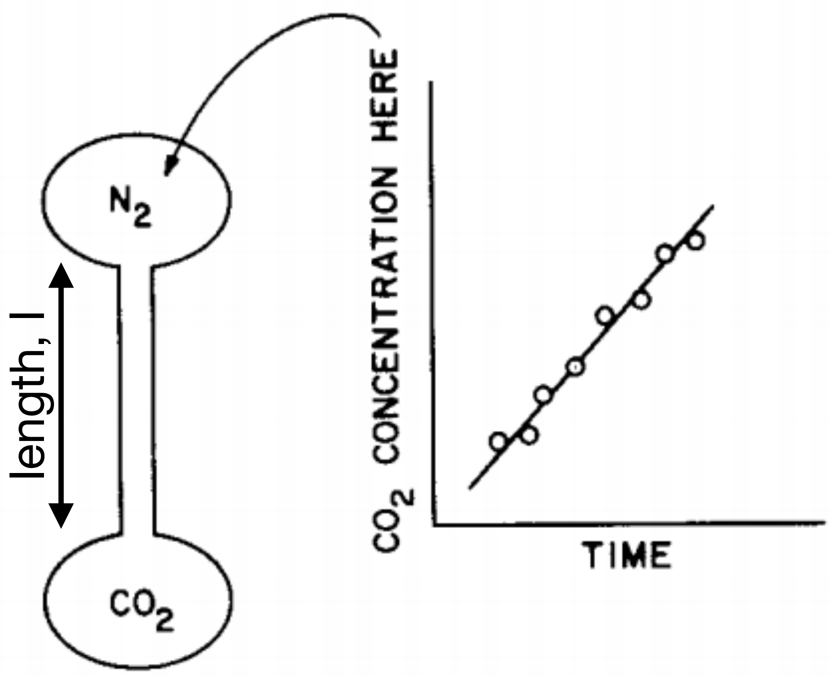
Diffusion vs. mass transfer coefficient



Rate of CO_2 increase $= k\left(\Delta C_{CO_2}\right)$

Rate of CO_2 increase $= D\dfrac{\left(\Delta C_{CO_2}\right)}{l}$

When do we use k and when do we use D?

Depends on the value of *l*
- large *l*, use *D*
- Interface (small *l*), use *k*

Depends on whether the system is well-mixed or not
- Well-mixed, use *k*
- Not well-mixed, use *D*

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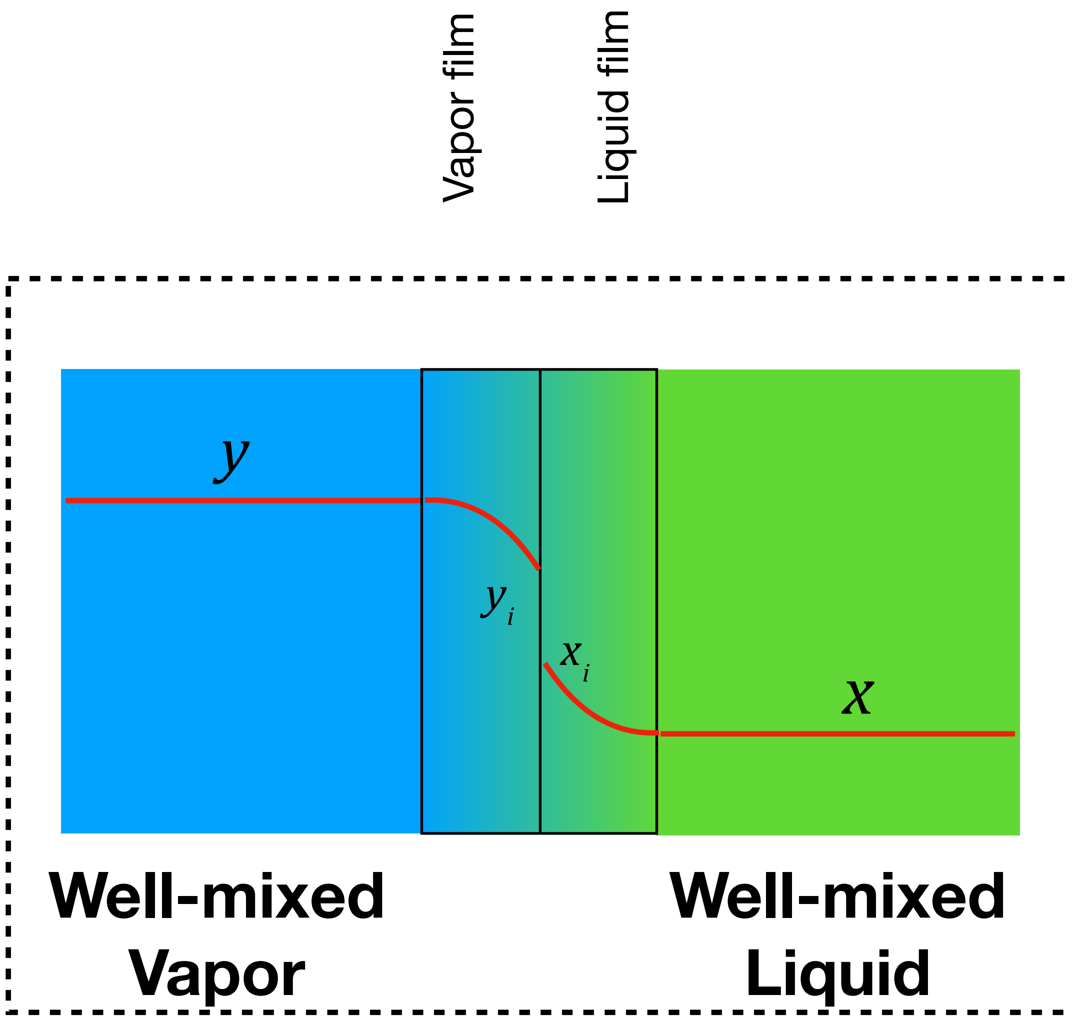
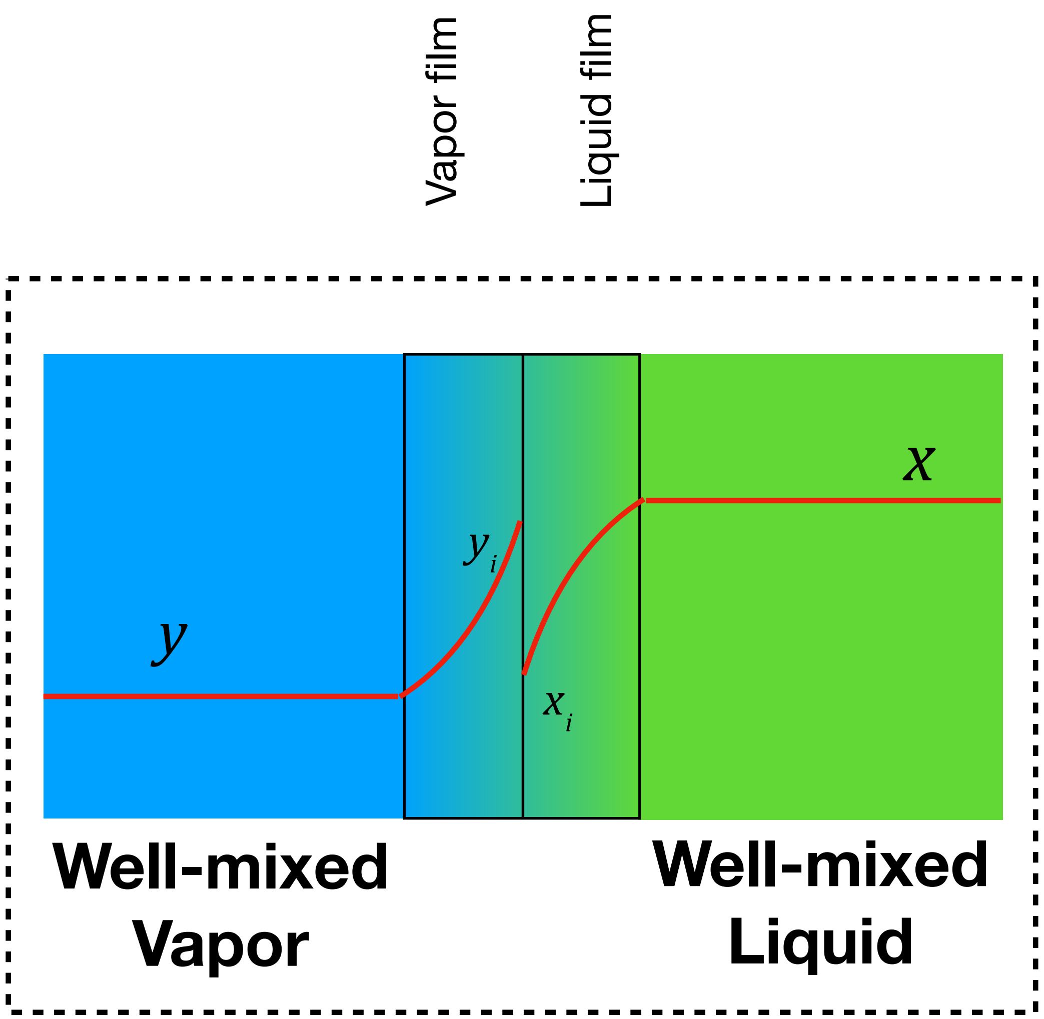
The concept of mass transfer coefficient

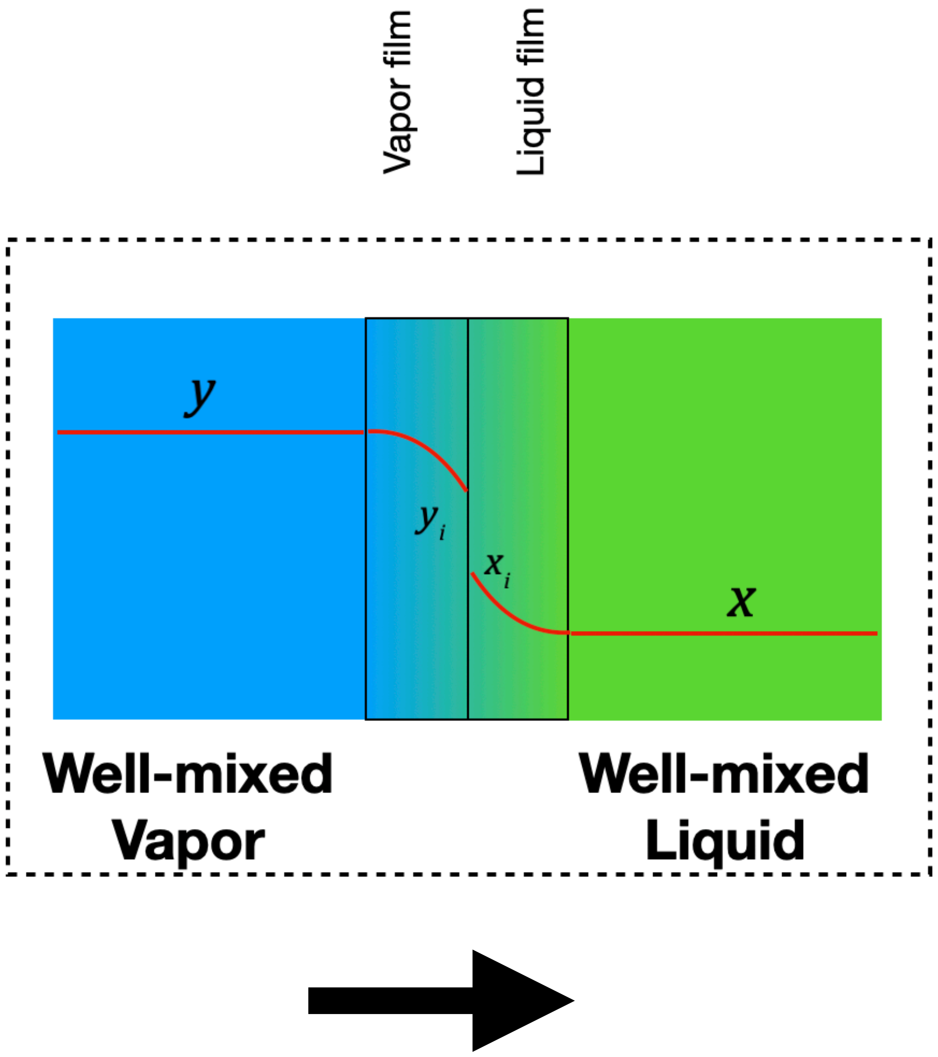


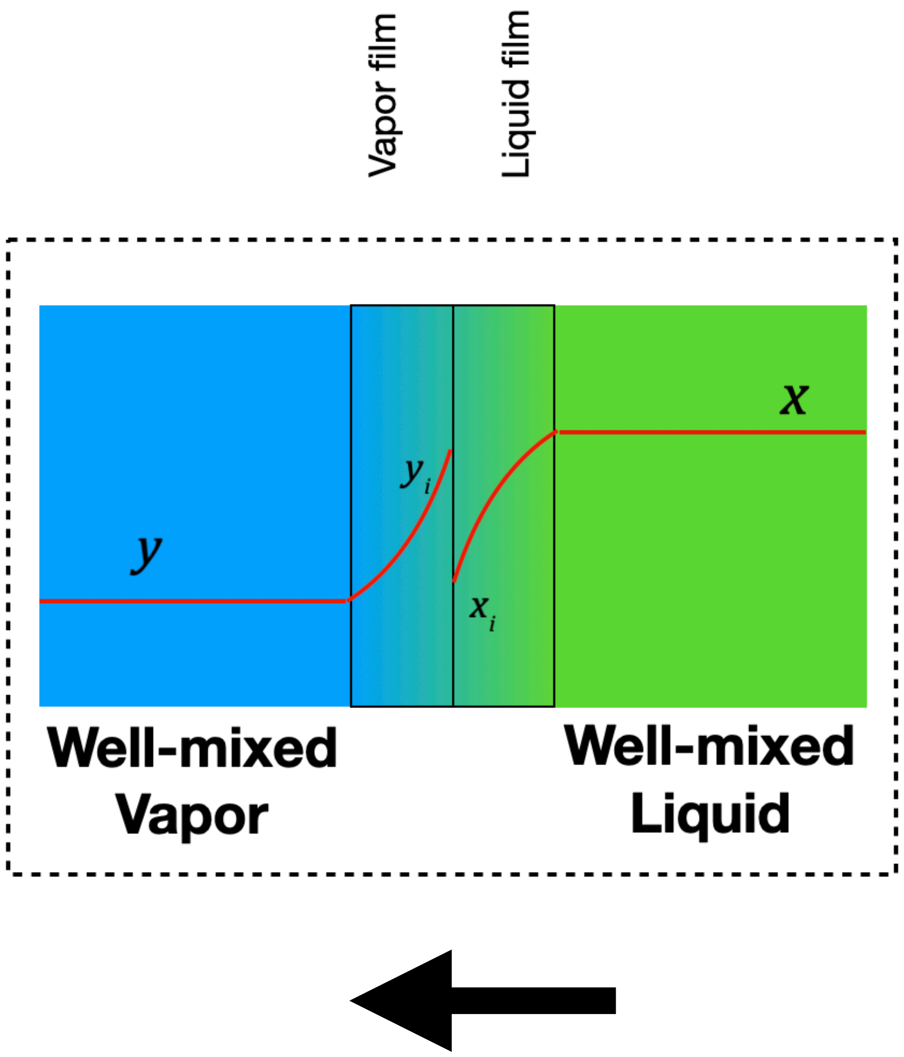


$$y_i = m x_i$$ at the interface

$$m > 1$$

Calculation of mass transfer rate





$$transfer \quad rate = N = k_y A(y - y_i) = k_x A(x_i - x)$$

$$transfer \quad rate = N = k_y A(y_i - y) = k_x A(x - x_i)$$

The overall resistance to mass transfer lies in the two films

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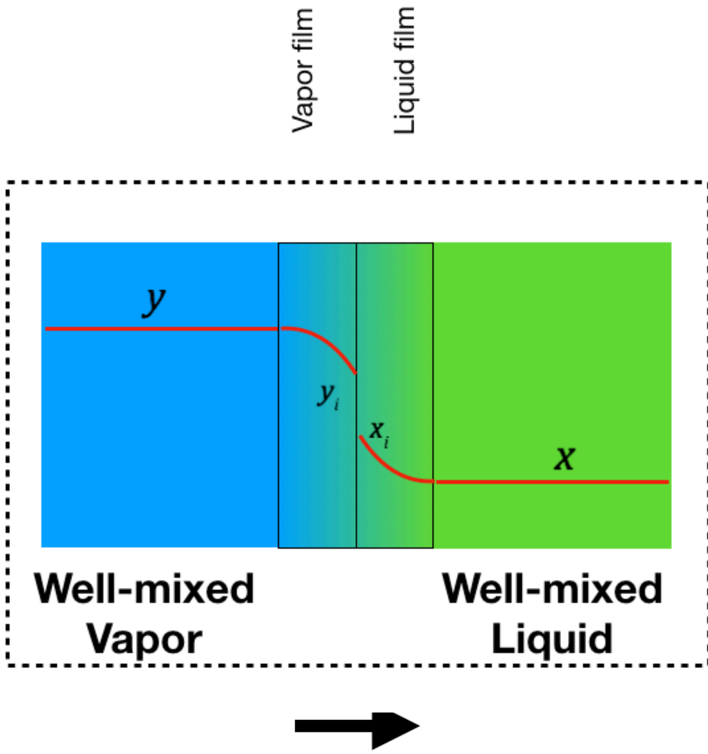
Overall mass transfer coefficient



$$N = k_y A(y - y_i) = k_x A(x_i - x)$$

$$y_i = mx_i$$

Usually y_i and x_i are not known

In this case,

$$N = K_y A(y - mx) = K_x A\left(\frac{y}{m} - x\right)$$

K_y and K_x are overall mass transfer coefficients

$$y - y_i = y - mx_i = \frac{N}{k_y A}$$

$$x_i - x = \frac{N}{k_x A} \qquad mx_i - mx = \frac{Nm}{k_x A}$$

$$y - mx_i + mx_i - mx = \frac{N}{k_y A} + \frac{Nm}{k_x A}$$

$$y - mx = \frac{N}{K_y A} \qquad y - mx = \frac{N}{K_y A} = \frac{N}{A}\left(\frac{1}{k_y} + \frac{m}{k_x}\right)$$

$$\frac{1}{K_y} = \left(\frac{1}{k_y} + \frac{m}{k_x}\right)$$

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

$$\frac{1}{K_x} = \frac{1}{mk_y} + \frac{1}{k_x}$$

$$K_x = mK_y$$

Correlations for mass transfer coefficients

$$Sh = \frac{kl}{D}$$

l is the characteristic length-scale (bubble diameter, plate width, etc.)

$$Sh = f\left(\mathrm{Re}, Sc\right) \qquad \mathrm{Re} = \frac{Dv\rho}{\mu} \qquad Sc = \frac{\mu}{\rho D}$$

- Schmidt number in gases ~1
- Schmidt numer in liquids ~ 10^3

Table 8.3-2 *Selected mass transfer correlations for fluid–fluid interfaces*[a]

Physical situation	Basic equation[b]	Key variables	Remarks
Liquid in a packed tower	$k\left(\frac{1}{\nu g}\right)^{1/3} = 0.0051\left(\frac{v^0}{a\nu}\right)^{0.67}\left(\frac{D}{\nu}\right)^{0.50}(ad)^{0.4}$	a = packing area per bed volume d = nominal packing size	Probably the best available correlation for liquids; tends to give lower value than other correlations
	$\frac{kd}{D} = 25\left(\frac{dv^0}{\nu}\right)^{0.45}\left(\frac{\nu}{D}\right)^{0.5}$	d = nominal packing size	The classical result, widely quoted; probably less successful than above
	$\frac{k}{v^0} = a\left(\frac{dv^0}{\nu}\right)^{-0.3}\left(\frac{D}{\nu}\right)^{0.5}$	d = nominal packing size	Based on older measurements of height of transfer units (HTUs); a is of order one
Gas in a packed tower	$\frac{k}{aD} = 3.6\left(\frac{v^0}{a\nu}\right)^{0.70}\left(\frac{\nu}{D}\right)^{1/3}(ad)^{-2.0}$	a = packing area per bed volume d = nominal packing size	Probably the best available correlation for gases
	$\frac{kd}{D} = 1.2(1-\varepsilon)^{0.36}\left(\frac{dv^0}{\nu}\right)^{0.64}\left(\frac{\nu}{D}\right)^{1/3}$	d = nominal packing size ε = bed void fraction	Again, the most widely quoted classical result

Problem:

A absorption column tray is contacting solvent with a gas. Calculate the overall mass transfer coefficient.

At interface, $y_i = m x_i$ $\quad m = 200 \quad k_x = 0.01 \ \frac{\text{mole}}{\text{m}^2\text{s}} \quad k_y = 1 \ \frac{\text{mole}}{\text{m}^2\text{s}}$

$$K_x = k_x = 0.01 \ \frac{mole}{m^2 s}$$

$$K_y = K_x / m = 0.01/200 = 5 * 10^{-5} \ \frac{mole}{m^2 s}$$

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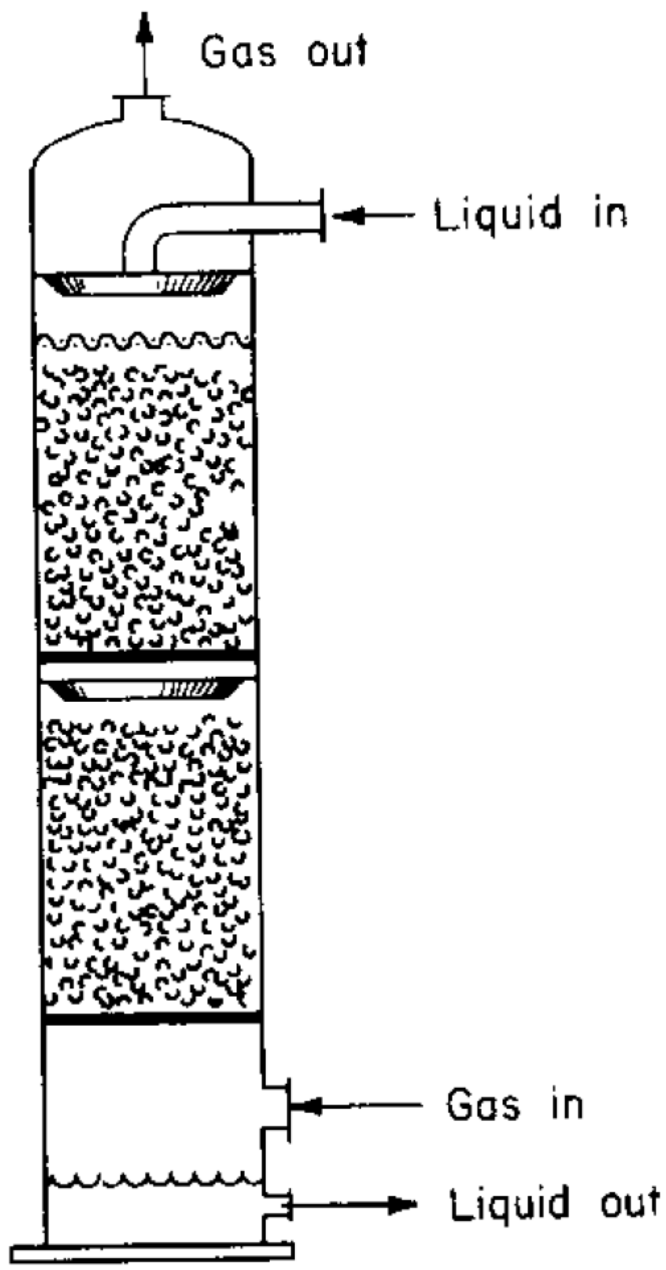
Packed column vs trays

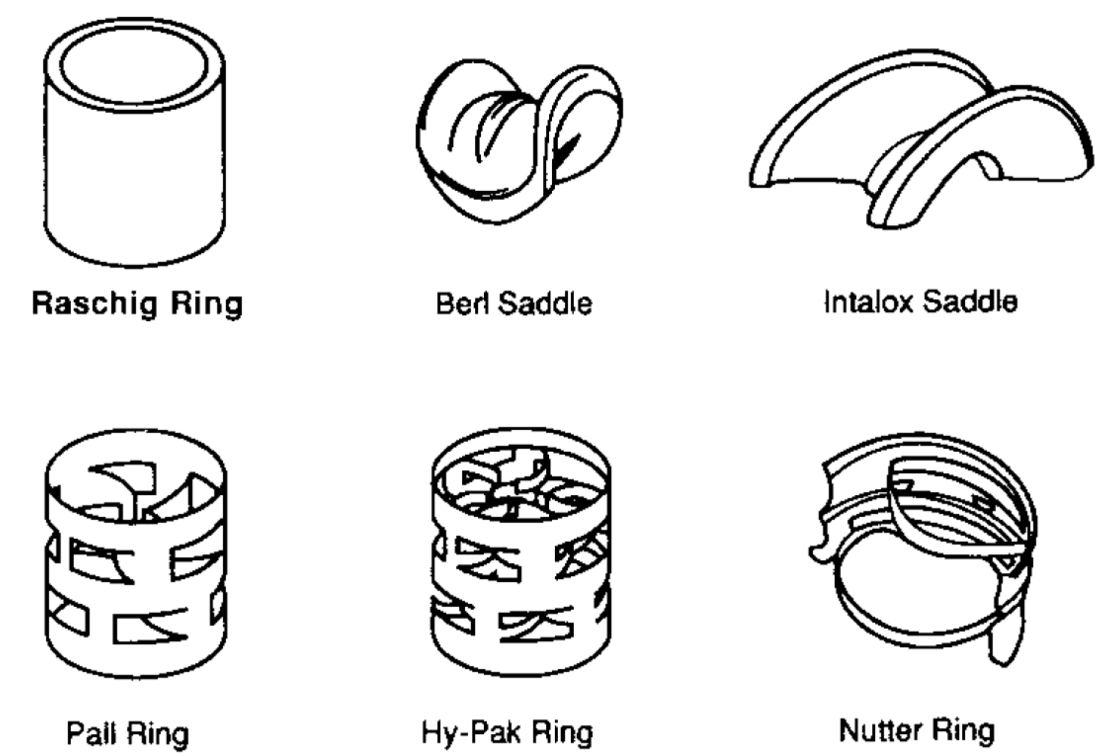
Packed towers are becoming more popular replacing equilibrium stages (trays or plates).

	Packed column	Trays/plates
Column diameter	Low (less than 0.6 m)	
Corrosion	Better for corrosive system (plastic, ceramic, metal alloys packing)	
Pressure drop	Lower (very important for vacuum distillation)	
Foaming	Better for foaming liquid	
Liquid flow	High (Not suitable for low flow rate)	
Liquid holdup	Low (Ideal for toxic and flammable liquids)	
Equipment cost		Slightly lower
Ease of cleaning		Easier to clean (better for fouling mixture)
Internal cooling/ heating		Easier
Side streams		Easier

Packed absorption column



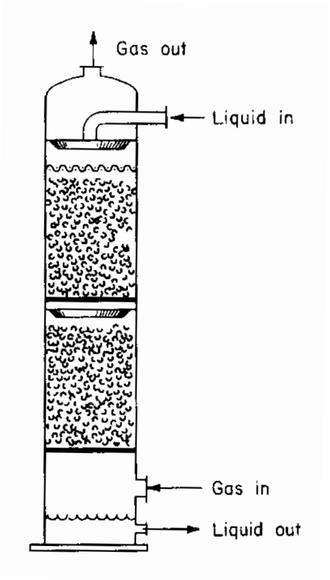
Packing must be properly held to utilize the entire column



Popular random packing materials optimized for high surface area and fast flow

Packing must be properly held to utilize the entire column

Effective number of stages in packed column



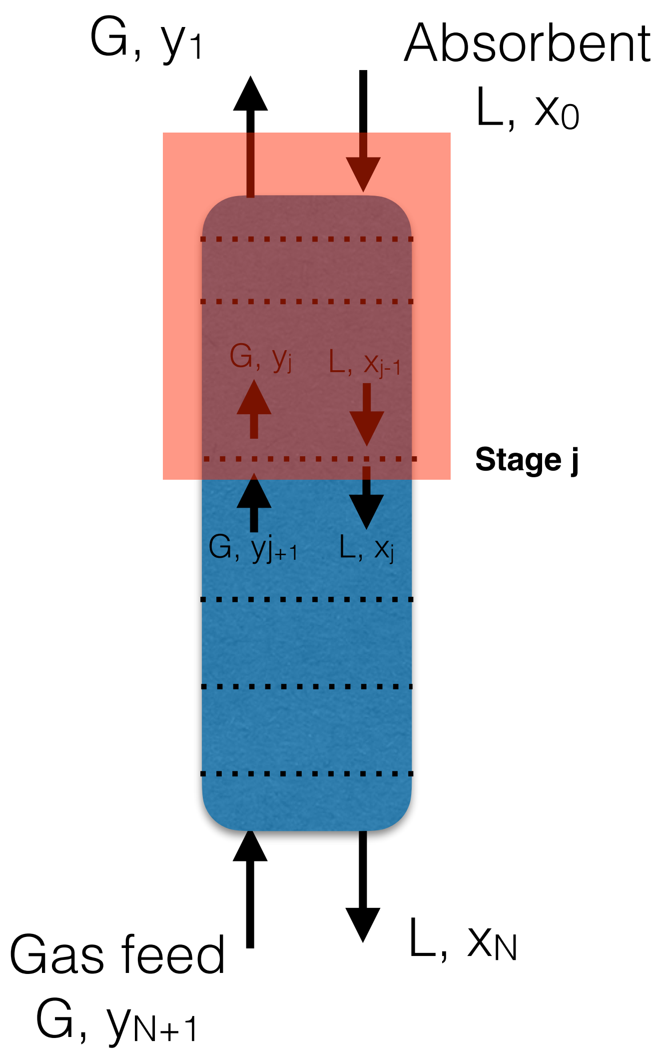
HTU: Height of transfer unit

NTU: Number of transfer unit

$$Height\ of\ packed\ column = h = HTU * NTU$$

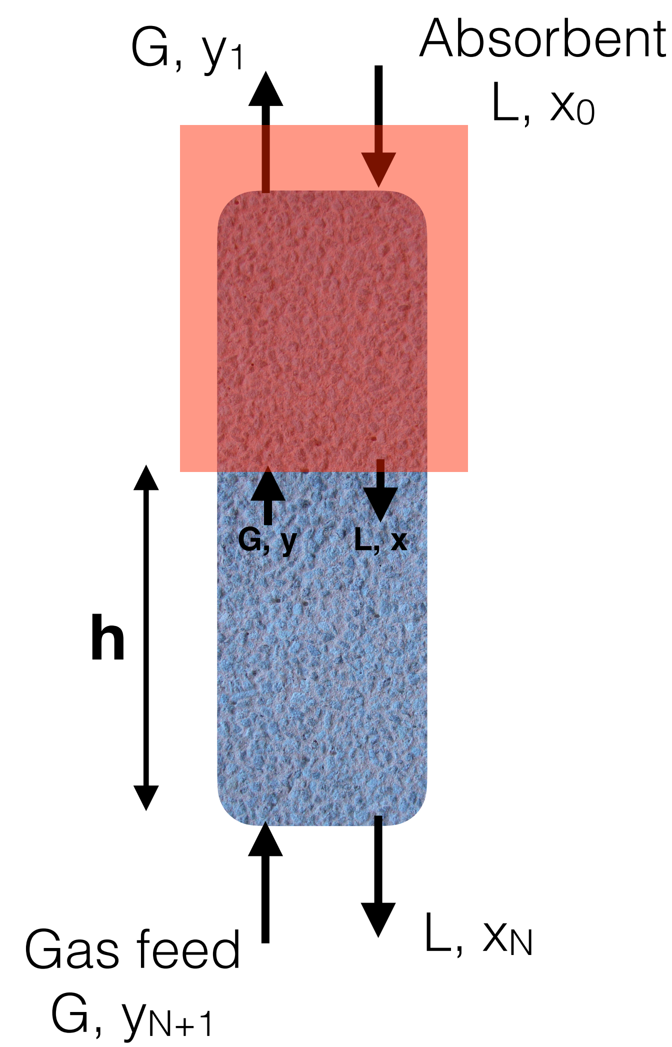
Dilute absorption in packed column

Staged column



$$y = \frac{L}{G}x + (y_1 - \frac{L}{G}x_0)$$

Packed column



$$y = \frac{L}{G}x + (y_1 - \frac{L}{G}x_0)$$

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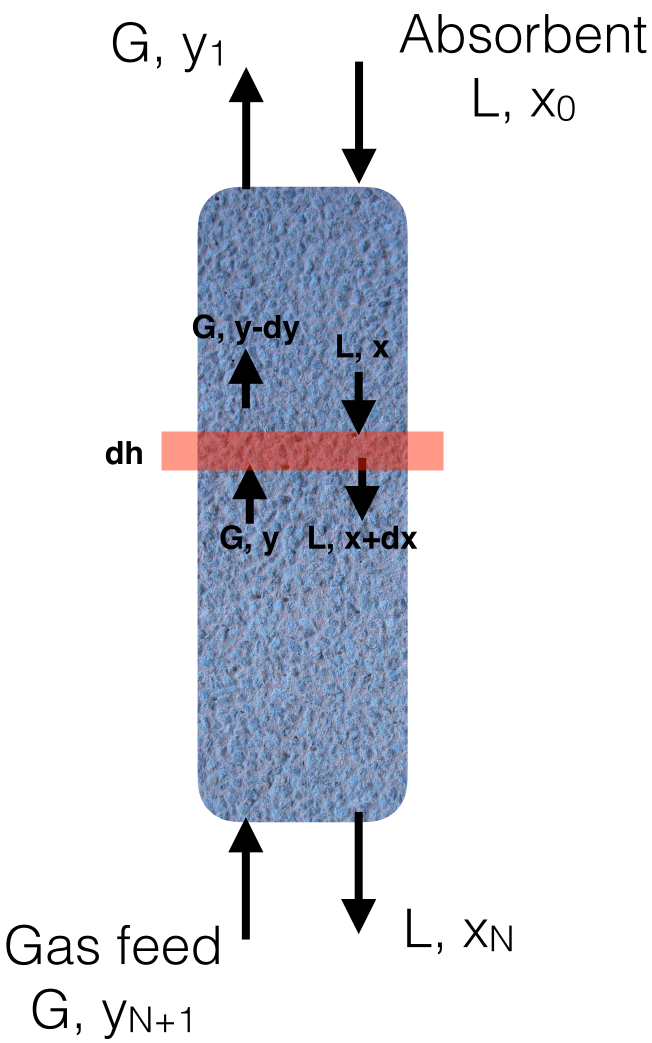
Dilute absorption in packed column

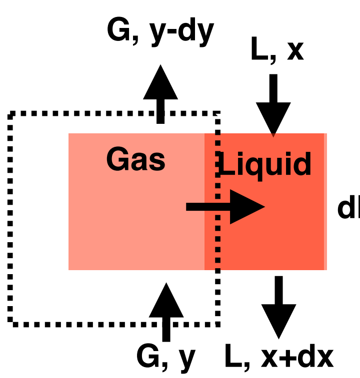


Overall balance on the element

Accumulation = in - out

$$0 = (Gy + Lx) - (G(y - dy) + L(x + dx))$$

$$Gdy = Ldx$$



Applying mass transfer concept

Accumulation = in - out

$$0 = Gy - G(y - dy) - K_y(y - y^*)aAdh \qquad y^* = mx$$

a = surface area per unit volume

Adh = volume available for mass exchange

$$Gdy = K_y aA(y - y^*)dh$$

$$\frac{G}{K_y aA}\frac{dy}{(y - y^*)} = dh$$

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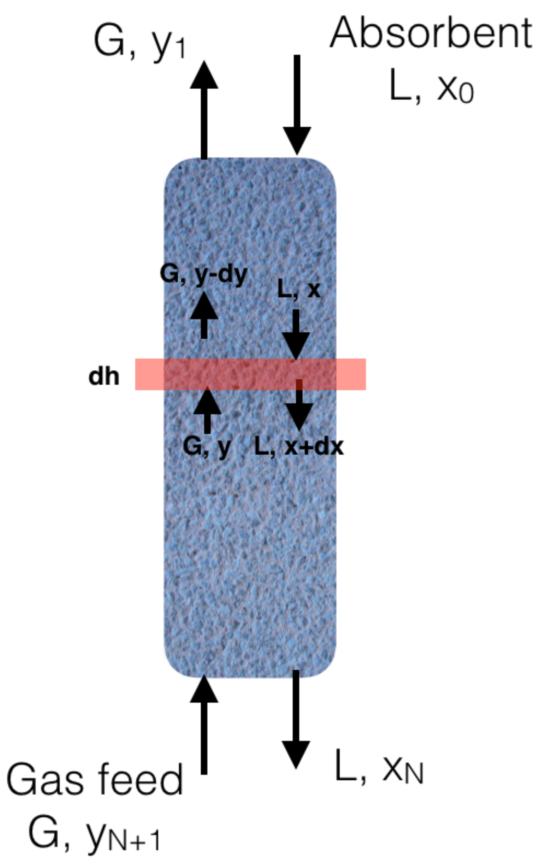
Dilute absorption in packed column



$$h=\frac{G}{K_y aA}\left[\left(\frac{1}{1-\frac{mG}{L}}\right)\ln\left(\frac{y_{N+1}-mx_N}{y_1-mx_0}\right)\right]$$

$$Height\ \ of\ \ packed\ \ column=h=HTU*NTU$$

$$HTU=\frac{G}{K_y aA}$$

Typically HTU is between 0.3 to 1 meter

$$NTU=\left(\frac{1}{1-\frac{mG}{L}}\right)\ln\left(\frac{y_{N+1}-mx_N}{y_1-mx_0}\right)$$

Useful empirical correlations for HTU

$$HTU = \frac{G}{K_y aA} = \frac{a_G W_G^b Sc_G^{0.5}}{W_L^c}$$

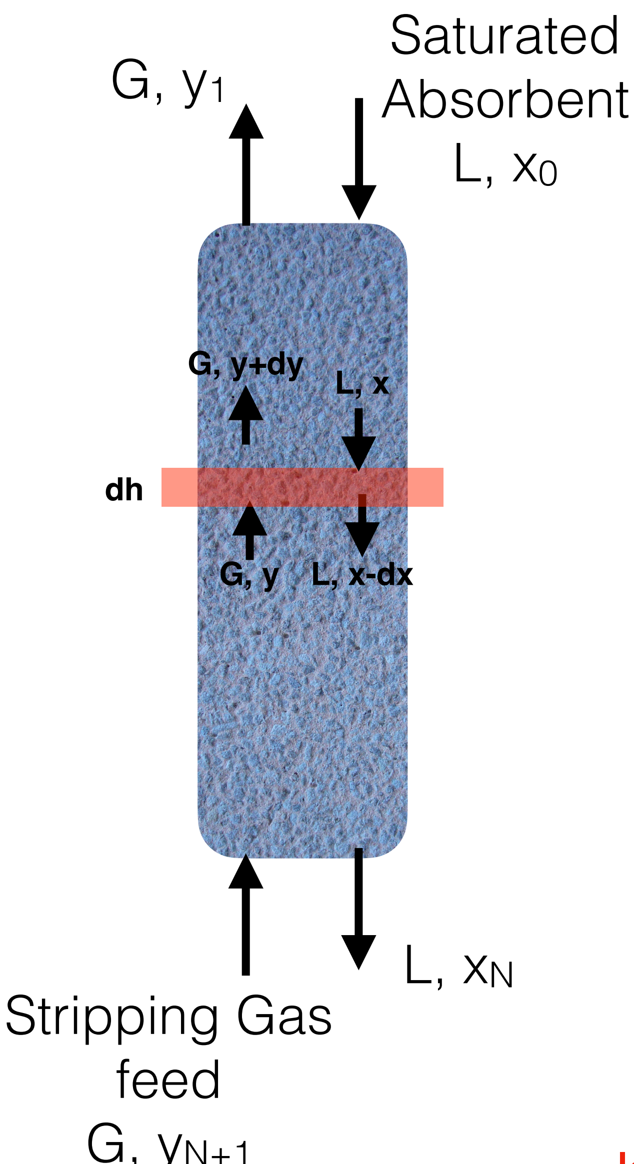
$$HTU = \frac{L}{K_x aA} = a_L Sc_L^{0.5} \left(\frac{W_L}{\mu} \right)^d$$

- HTU is in feet.
- W_G and W_L are flow in lb/(h·ft²)

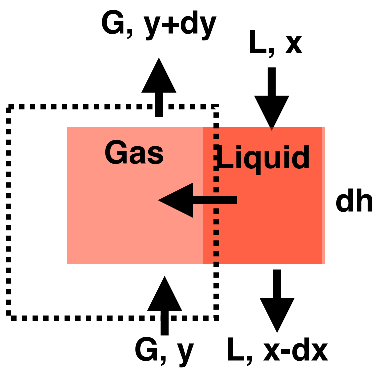
				Range for Eq. (16-40a)			
Packing	a_G	b	c	W_G	W_L	a_L	D
Raschig rings							
3/8 in.	2.32	0.45	0.47	200–500	500–1500	0.0018	0.46
1	7.00	0.39	0.58	200–800	400–500	0.010	0.22
1	6.41	0.32	0.51	200–600	500–4500	—	—
2	3.82	0.41	0.45	200–800	500–4500	0.012	0.22
Berl saddles							
1/2 in.	32.4	0.30	0.74	200–700	500–1500	0.0067	0.28
1/2	0.811	0.30	0.24	200–700	1500–4500	—	—
1	1.97	0.36	0.40	200–800	400–4500	0.0059	0.28
3/2	5.05	0.32	0.45	200–1000	400–4500	0.0062	0.28

From textbook (Wankat)

Dilute stripping in packed column



Accumulation = in - out



$$0 = Gy + K_y(y^* - y)aAdh - G(y+dy)$$

$$Gdy = K_y aA(y^* - y)dh$$

$$\frac{G}{K_y aA}\frac{dy}{(y^* - y)} = dh$$

$$h = \frac{G}{K_y aA}\left[\left(\frac{1}{\frac{mG}{L} - 1}\right)\ln\left(\frac{mx_0 - y_1}{mx_N - y_{N+1}}\right)\right]$$

Stripping, written in gas-phase mass transfer

Is it related to the absorption equation???

$$h = \frac{G}{K_y aA}\left[\left(\frac{1}{1 - \frac{mG}{L}}\right)\ln\left(\frac{y_{N+1} - mx_N}{y_1 - mx_0}\right)\right]$$

Exactly same as the one for absorption!!

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