THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

Mass Transfer-I

Gas Absorption (Continue…)

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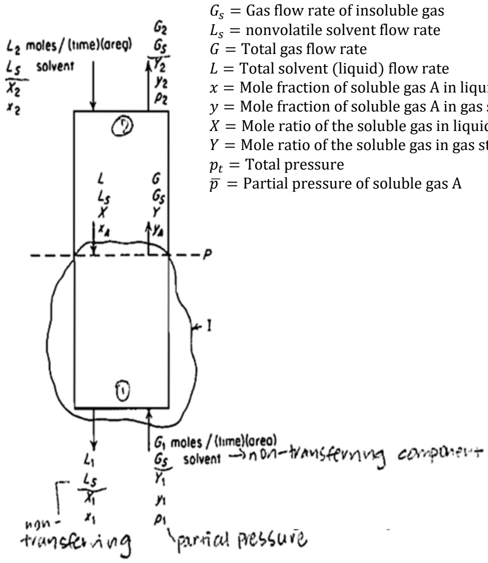
Gas Absorption (Continue…)

One component transfer: Material balance(counter flow)



G_s = Gas flow rate of insoluble gas
L_s = nonvolatile solvent flow rate
G = Total gas flow rate
L = Total solvent (liquid) flow rate
x = Mole fraction of soluble gas A in liquid stream
y = Mole fraction of soluble gas A in gas stream
X = Mole ratio of the soluble gas in liquid stream
Y = Mole ratio of the soluble gas in gas stream
p_t = Total pressure
$\bar{p}$ = Partial pressure of soluble gas A

For gas stream

$$\boldsymbol{Y = \frac{y}{1-y} = \frac{\bar{p}}{p_t - \bar{p}}}$$

$$\boldsymbol{G_s = G(1-y) = \frac{G}{1-Y}}$$

Similarly for liquid stream

$$\boldsymbol{X = \frac{x}{1-x}}$$

$$\boldsymbol{L_s = G(1-x) = \frac{L}{1-X}}$$

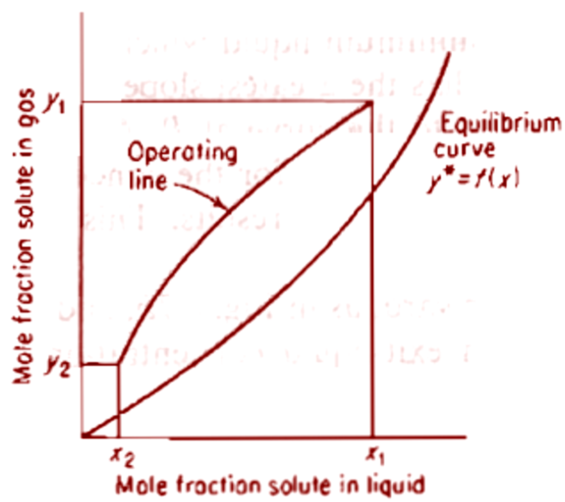
Cont…

Envelope 1

$$G_s(Y_1 - Y) = L_s(X_1 - X)$$

The equation of operating line is

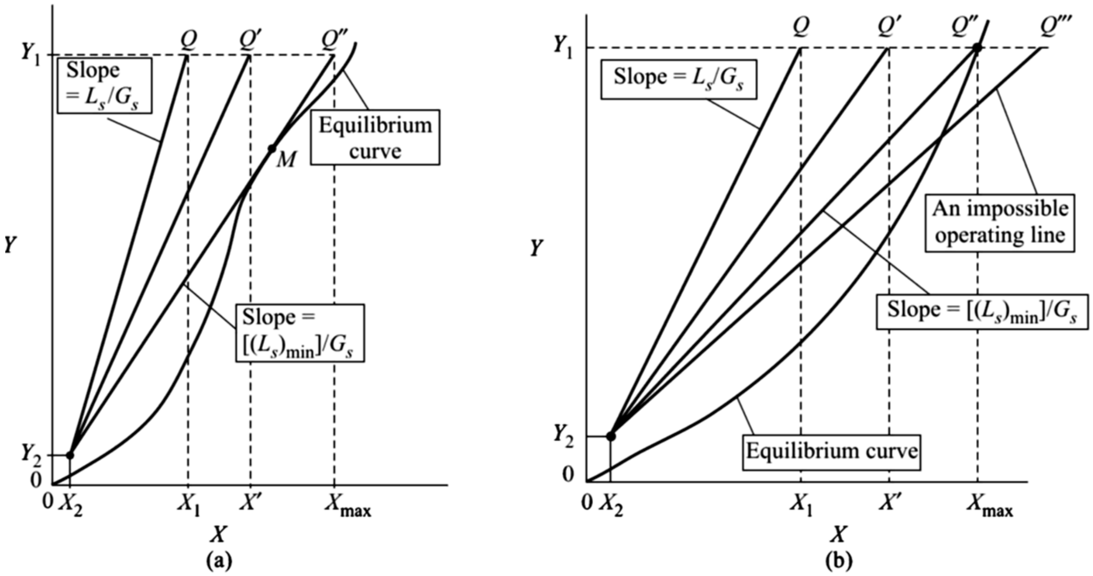
$$G_s\left(\frac{y_1}{1-y_1} - \frac{y}{1-y}\right)$$
$$= G_s\left(\frac{\overline{p_1}}{p_t - \overline{p_1}} - \frac{\bar{p}}{p_t - \bar{p}}\right)$$
$$= L_s\left(\frac{x_1}{1-x_1} - \frac{x}{1-x}\right)$$



The operating is straight in case of Mole ratio, Hence mole ratio is convenient for the analysis

Cont…

Minimum liquid-gas ratio- Graphical determination



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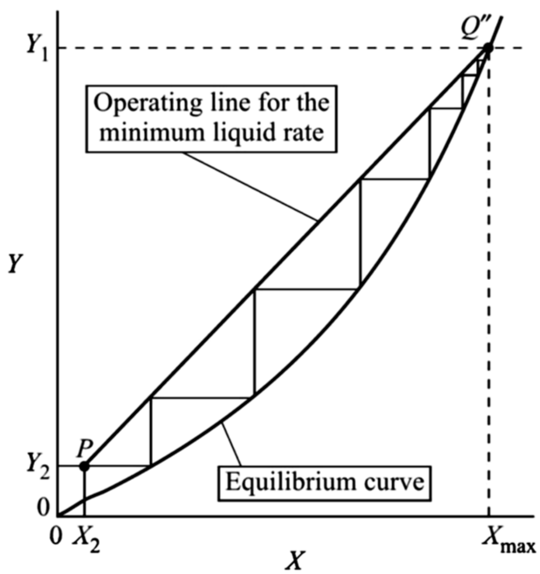

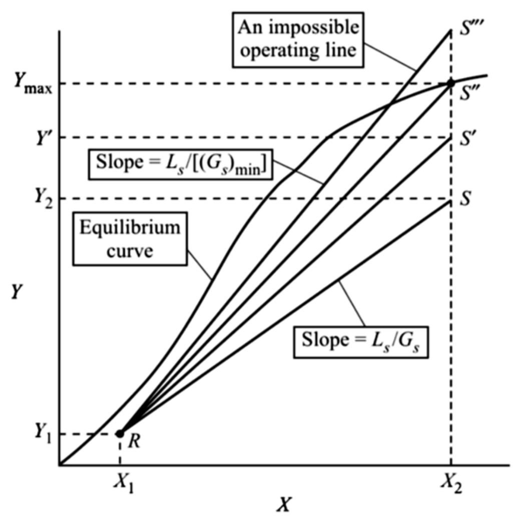

Infinite number of plates required for the minimum liquid rate

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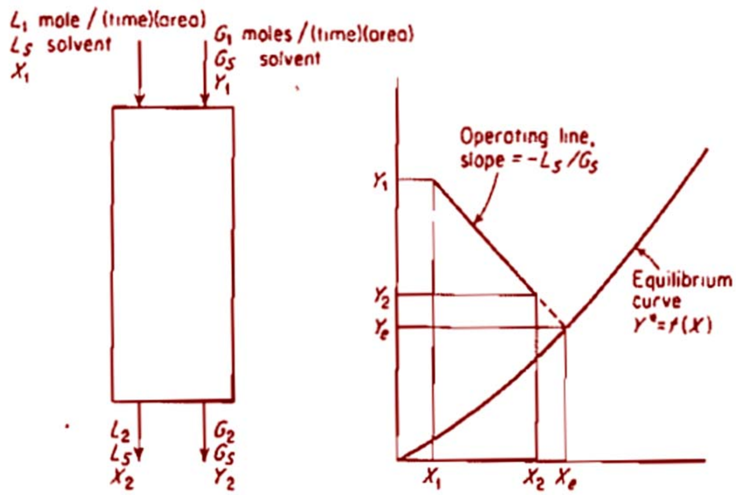
Co-current flow arrangement



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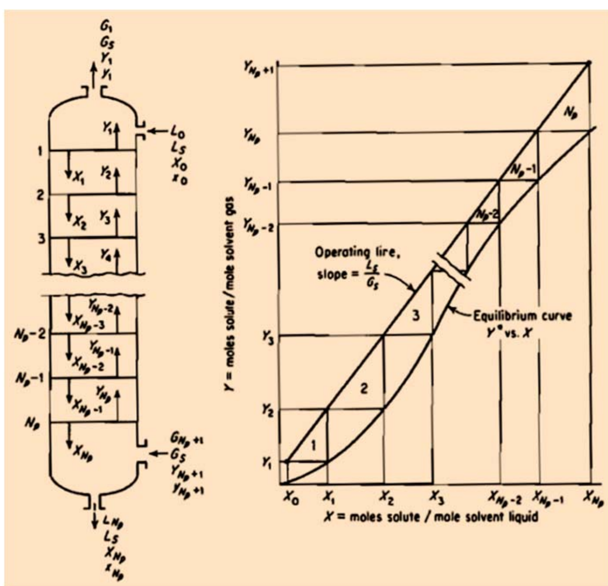
Counter current multistage operation: one component transferred



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Example-1

(*Calculation of the minimum solvent rate*) In a petrochemical plant, a gas containing 4% *cyclo*-hexane and 96% inerts has to be treated with a non-volatile absorption oil in a packed tower. It is required to remove 98% of the *cyclo*-hexane of the feed gas. The feed solvent is free from *cyclo*-hexane. If the feed gas rate is 80 kmol per hour, calculate the minimum solvent rate. The equilibrium relation is given as

$$Y = \frac{0.2\,X}{1+0.8\,X}$$

The following equilibrium data are calculated from the given equilibrium relation.

X	0	0.01	0.03	0.05	0.07	0.09	0.12
Y	0	0.00198	0.00586	0.0097	0.0113	0.0168	0.0219

Cont…

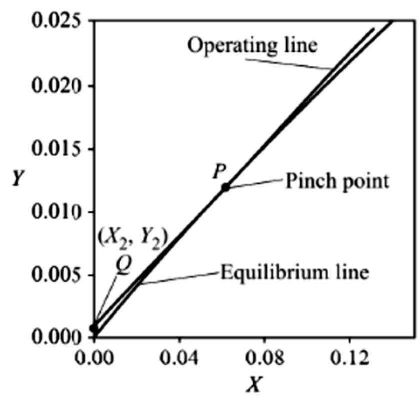
Solution

Given: feed gas rate = 80 kmol/h; concentration of *cyclo*-hexane, y_1 = 0.04 (mole fraction).

Rate of input of the solute (*cyclo*-hexane) = (80)(0.04) = 3.2 kmol/h; carrier gas in, G_s = 80 – 3.2 = 76.8 kmol/h; 98% of the solute is absorbed, and 2% leaves the tower with the carrier gas.

$$Y_1 = \frac{y_1}{1-y_1} = \frac{0.04}{1-0.04} = 0.0417$$

$$Y_2 = (0.02)Y_1 = 0.000834$$



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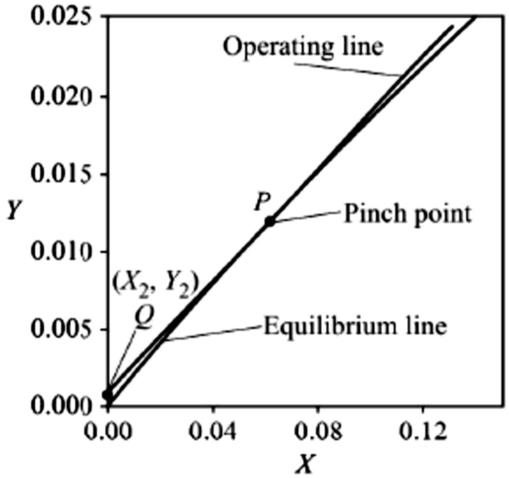


Also $X_2 = 0$ (the feed solvent is solute-free). (X_2, Y_2) $\rightarrow$ (0, 0.000834)

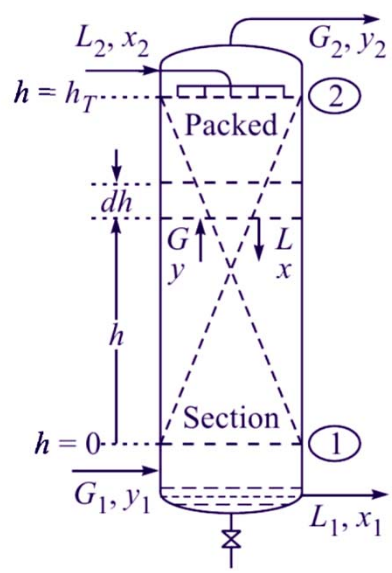
(i) Plot the equilibrium data calculated above on the X–Y plane; (ii) locate the point $Q(X_2, Y_2)$; (iii) draw the operating line through (X_2, Y_2) that touches the equilibrium line. The point of tangency P is the *pinch point*. This operating line QP corresponds to the *minimum liquid rate*; its slope is $(L_s/G_s)_{min} = 0.19$.

Given: $G_s = 76.8$ kmol/h; therefore, the minimum liquid rate, $(L_s)_{min} = (76.8)(0.19) = \boxed{14.6 \text{ kmol/h}}$

Design of packed tower (continuous contact equipment)

G_s = Gas flow rate of insoluble gas
L_s = nonvolatile solvent *flow rate*
h_T = Height of the packed tower
G = Total gas flow rate
L = Total solvent (liquid) flow rate
N_A = local flux
k_y = The individual gas-phase mass transfer coefficient
dh = The hight of elementary packed volume
x = Mole fraction of soluble gas A in liquid stream
y = Mole fraction of soluble gas A in gas stream
X = Mole ratio of the soluble gas in liquid stream
Y = Mole ratio of the soluble gas in gas stream

Subscripts
1 = For quantities at section 1
2 = For quantities at section 2



Cont…

Let N_A be the local flux and k_y be the individual gas phase mass transfer coefficient

Packed volume of differential cross section area = (1)×(***dh)***

Interfacial area of contact in the differential section = $(\bar{a})\times(1)\times(dh)$

Rate of mass transfer of the solute = $(\bar{a})\times(N_A)\times(dh)$

A mass balance over the elementary section of the bed yields

$$(\bar{a})(dh)(N_A) = -d(G'y) = -G'dy - ydG'$$

$$-dG' = (\bar{a})(dh)(N_A)$$

$$N_A = k_y(y - y_i)$$

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Cont…

$$(\bar{a})(dh)N_A(1 - y) = -G'dy$$

$$dh = \frac{-G'dy}{k_y\bar{a}(1-y)(y-y_i)}$$

$$h_T = \int_0^{h_T} dh = -\int_{y_1}^{y_2} \frac{G'dy}{k_y\bar{a}(1-y)(y-y_i)} = \int_{y_2}^{y_1} \frac{G'dy}{k_y\bar{a}(1-y)(y-y_i)}$$

Evaluation of the above integral gives the height of the packing. The integration is not straight-forward, since the interfacial concentration y_i is not explicitly known as a function of the variable y. The following steps should be followed in general (McNulty, 1994):

The above integral will give the height of packing using following graphical method

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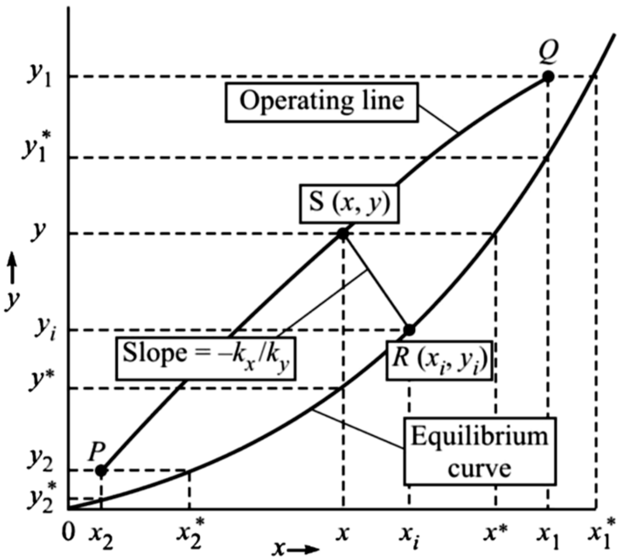
(a) Draw the equilibrium curve on the x-y plane for the particular gas–liquid system.
(b) Draw the operating line from the material balance equation,



Operating line equation

$$G_s\left(\frac{y}{1-y}-\frac{y_2}{1-y_2}\right) = L_s\left(\frac{x}{1-x}-\frac{x_2}{1-x_2}\right)$$

$$Y = \frac{y}{1+y},\quad X = \frac{x}{1-x}$$

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Cont…

Refer to previous equation

$$h_T = \int_0^{h_T} dh = -\int_{y_1}^{y_2} \frac{G'\,dy}{k_y\bar{a}(1-y)(y-y_i)} = \int_{y_2}^{y_1} \frac{G'\,dy}{k_y\bar{a}(1-y)(y-y_i)}$$

It can be rewrite in the following form

$$h_T = \int_{y_2}^{y_1} \frac{G'\,y_{iBM}\,dy}{k_y\,\bar{a}\,y_{iBM}(1-y)(y-y_i)} = \int_{y_2}^{y_1} \frac{G'(1-y)_{iM}\,dy}{k_y\,\bar{a}(1-y)_{iM}(1-y)(y-y_i)}$$

where y_{iBM} is the log mean value of y_B [= $(1 - y)$] defined as follows:

$$y_{iBM} = (1-y)_{iM} = \frac{(1-y_i)-(1-y)}{\ln\dfrac{1-y_i}{1-y}}$$

Cont…

The height of the transfer unit based on the individual gas-phase coefficient or the 'height of an individual gas-phase transfer unit' is denoted by $\boldsymbol{H_{tG}}$. Hence, we can rewrite above equation in the following form

$$h_T = \frac{G'}{k_y a(1-y)_{iM}} \int_{y_2}^{y_1} \frac{(1-y)_{iM}\, dy}{(1-y)(y-y_i)} = H_{tG} \int_{y_2}^{y_1} \frac{(1-y)_{iM}\, dy}{(1-y)(y-y_i)}$$

$$H_{tG} = \frac{G'}{k_y \bar{a}(1-y)_{iM}} = \frac{G'}{k'_y \bar{a}}$$

$$\int_{y_2}^{y_1} \frac{(1-y)_{iM}\, dy}{(1-y)(y-y_i)} \Rightarrow \text{No. of gas phase transfer unit}$$

$$h_T = H_{tG}\, N_{tG}$$

$\boldsymbol{h_T}$ = Height of the transfer unit based on the individual gas-phase coefficient
$\boldsymbol{N_{tG}}$ = Number of gas phase transfer units

Cont…

If the overall gas-phase mass transfer coefficient is used to express the rate of mass transfer, the height of the packing can be obtained from the following equation:

$$h_T = \int_{y_2}^{y_1} \frac{G' y^*_{BM}\, dy}{K_y \bar{a}\, y^*_{BM}(1-y)(y-y^*)} = \frac{G'}{K_y \bar{a}\, y^*_{BM}} \int_{y_2}^{y_1} \frac{y^*_{BM}\, dy}{(1-y)(y-y^*)} = H_{tOG}\, N_{tOG}$$

where

$$H_{tOG} = \text{height of an overall gas-phase transfer unit} = \frac{G'}{K_y \bar{a}\, y^*_{BM}}$$

$$N_{tOG} = \text{number of overall gas-phase transfer units} = \int_{y_2}^{y_1} \frac{y^*_{BM}\, dy}{(1-y)(y-y^*)}$$

and $$y^*_{BM} = (1-y)^*_M = \frac{(1-y^*)-(1-y)}{\ln[(1-y^*)/(1-y)]}$$

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Cont…

The height of the packing can also be determined using other types of individual mass transfer coefficients (k_x, k_G, k_L, K_y, K_x, etc.). The design equations given below can be derived following the above procedure.

$$h_T = \int_{x_2}^{x_1} \frac{L'\,dx}{k_x\bar{a}(1-x)(x_i-x)} = \int_{y_2}^{y_1} \frac{G'\,dy}{k_G\,\bar{a}\,P(1-y)(y-y_i)} = \int_{x_2}^{x_1} \frac{L'\,dx}{k_L\,\bar{a}\,(C)_{\text{av}}(1-x)(x_i-x)}$$

The height of the packing for a *stripping column* can be obtained in a similar way. But here $y_2 > y_1$ and the gas-phase driving force at any point is $y_i - y$.

$$\boxed{h_T = \int_{y_1}^{y_2} \frac{G'\,dy}{k_y\,\bar{a}\,(1-y)(y_i-y)}}$$

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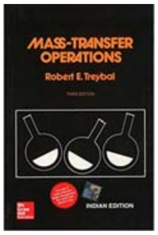
Expressions for HTUs and NTUs

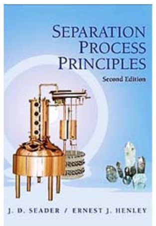
Driving force	*Height of a Transfer Unit (HTU)*			*Number of Transfer Units (NTU)*	
	Symbol	*DANB*	*ECD*	*Symbol*	
$y - y_i$	H_{tG}	$\frac{G'}{k_y\,\bar{a}\,(1-y)_{iM}}$	$\frac{G'}{k'_y\,\bar{a}}$	N_{tG}	$\int_{y_2}^{y_1} \frac{(1-y)_{iM}\,dy}{(1-y)(y-y_i)}$
$y - y^*$	H_{tOG}	$\frac{G'}{K_y\,\bar{a}\,(1-y)^*_M}$	$\frac{G'}{K'_y\,\bar{a}}$	N_{tOG}	$\int_{y_2}^{y_1} \frac{(1-y)^*_M\,dy}{(1-y)(y-y^*)}$
$Y - Y^*$	H_{tOG}	$\frac{G'_s}{K_Y\,\bar{a}}$	$\frac{G'_s}{K_Y\,\bar{a}}$	N_{tOG}	$\int_{Y_2}^{Y_1} \frac{dY}{(Y-Y^*)}$
$x_i - x$	H_{tL}	$\frac{L'}{k_x\,\bar{a}\,(1-x)_{iM}}$	$\frac{L'}{k'_x\,\bar{a}}$	N_{tL}	$\int_{x_2}^{x_1} \frac{(1-x)_{iM}\,dx}{(1-x)(x_i-x)}$
$x^* - x$	H_{tOL}	$\frac{L'}{K_x\,\bar{a}\,(1-x)^*_M}$	$\frac{L'}{K'_x\,\bar{a}}$	N_{tOL}	$\int_{x_2}^{x_1} \frac{(1-x)^*_M\,dx}{(1-x)(x^*-x)}$
$X^* - X$	H_{tOL}	$\frac{L'_s}{K_X\,\bar{a}}$	$\frac{L'_s}{K_X\,\bar{a}}$	N_{tOL}	$\int_{X_2}^{X_1} \frac{dX}{(X^*-X)}$

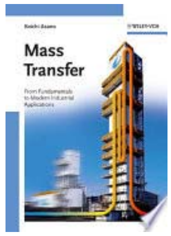
$$(1-y)_{iM} = \frac{(1-y_i)-(1-y)}{\ln[(1-y_i)/(1-y)]}; \qquad (1-y)^*_M = \frac{(1-y^*)-(1-y)}{\ln[(1-y^*)/(1-y)]}$$

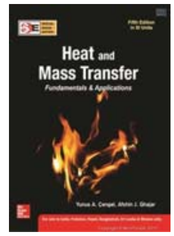
DANB: Diffusion of *A* through non-diffusing *B*; ECD: Equimolar counterdiffusion of *A* and *B*.

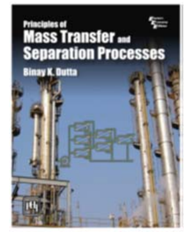
References

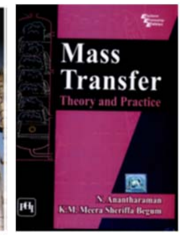












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Mass Transfer

Theories for Mass Transfer Coefficients

Lecture 9, 15.11.2017, Dr. K. Wegner

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

CHEMICAL ENGINEERING AND CHEMICAL PROCESS TECHNOLOGY – Vol. II - *Mass Transfer Operations: Absorption And Extraction* - José Coca, Salvador Ordóñez and Eva Díaz

MASS TRANSFER OPERATIONS: ABSORPTION AND EXTRACTION

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