UNIVERSITI SAINS MALAYSIA

First Semester Examination
2011/2012 Academic Session

January 2012

# EKC 217 – Mass Transfer
## *[Pemindahan Jisim]*

Duration : 3 hours
*[Masa : 3 jam]*

Please ensure that this examination paper contains SEVEN printed pages and FIVE printed pages of Appendix before you begin the examination.

*[Sila pastikan bahawa kertas peperiksaan ini mengandungi TUJUH muka surat yang bercetak dan LIMA muka surat Lampiran sebelum anda memulakan peperiksaan ini.]*

**Instruction:** Answer **ALL** (4) questions.

*[**Arahan:** Jawab **SEMUA** (4) soalan.]*

In the event of any discrepancies, the English version shall be used.

*[Sekiranya terdapat sebarang percanggahan pada soalan peperiksaan, versi Bahasa Inggeris hendaklah diguna pakai.]*

Answer ALL questions.
*Jawab SEMUA soalan.*

1. [a] An open beaker is filled with liquid benzene as shown in Figure Q.1.[a]. at 25°C. The evaporated benzene is carried away by dry air flowing gently across the opening of beaker at 25°C and 1 atm. The evaporated benzene is transferred through a stagnant air layer in the beaker. The vapor pressure of benzene at 25°C is 0.131 atm. Diffusivity of benzene in air at 25°C and 1atm is 0.0905 $cm^2/s$. Determine the initial rate of evaporation of benzene as a molar flux in $mol/cm^2$-s. Compute the initial mol-fraction profiles in the stagnant air layer for $z$ in the range of 0 - 0.5 cm.

*Suatu bikar terbuka dipenuhi dengan cecair benzena seperti yang ditunjukkan dalam Rajah S.1.[a] pada 25°C. Benzena yang tersejat dibawa oleh udara kering yang mengalir perlahan-lahan melalui pembukaan bikar pada 25°C dan 1 atm. Benzena yang tersejat dipindahkan melalui lapisan udara yang bertakung dalam bikar. Tekanan wap benzena pada 25°C ialah 0.131 atm. Kemeresapan benzena dalam udara pada 25°C dan 1 atm ialah 0.0905 $sm^2/s$. Tentukan kadar awal penyejatan benzena sebagai fluks molar dalam $mol/sm^2$.s. Kirakan profil pecahan-mol awal dalam lapisan udara bertakung untuk* z *dalam julat 0 - 0.5 sm.*

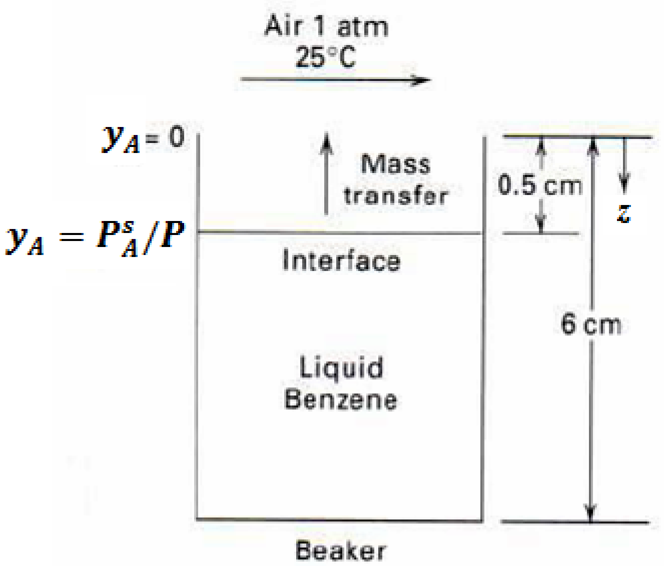


Figure Q.1.[a]. Evaporation of benzene to air
*Rajah S.1.[a]. Penyejatan benzena ke udara*

*[15 marks/markah]*

[b] $CO_2$ is stripped from water by air in a wetted wall tube. At a specific location in the stripper with pressure of 10atm and temperature of 25°C, the mass-transfer flux of $CO_2$ is 0.00022 mol/s-m$^2$. The partial pressure of $CO_2$ is 8.2 atm at the interface and 0.1atm in the bulk gas. The diffusivity of $CO_2$ in air at 10 atm and 25°C is 1.6 x 10$^{-2}$cm$^2$/s. Assuming turbulent flow of the gas, calculate the mass-transfer coeffient $k_c$ for the gas phase and the film thickness by the film theory.

*$CO_2$ dilucutkan daripada air menggunakan udara dalam tiub dinding basah. Di suatu lokasi tertentu dalam pelucut dengan tekanan 10 atm dan suhu 25 °C, fluks jisim pemindahan $CO_2$ ialah 0.00022 mol/s-m$^2$. Tekanan separa $CO_2$ adalah 8.2 atm pada antara muka dan 0.1 atm dalam gas pukal. Kemeresapan $CO_2$ dalam udara pada 10 atm dan 25 °C ialah 1.6 x 10$^{-2}$ sm$^2$/s. Andaikan aliran gelora gas, kirakan pekali pemindahan jisim $k_c$ bagi fasa gas dan ketebalan filem dengan menggunakan teori filem.*

*[10 marks/markah]*

2. [a] A tray tower is to be used to remove 95% of the ammonia from an entering air stream containing 5 mol% ammonia at 293 K and 1 atm. The entering pure water flow rate is 10.45 kgmol $H_2O$/h and the inert air flow rate is 4.41 kgmol air/h.

*Suatu turus dulang akan digunakan untuk menyingkirkan 95% amonia daripada aliran udara masuk yang mengandungi 5 mol% amonia pada 293 K dan 1 atm. Kadar aliran air tulen masuk ialah 10.45 kgmol $H_2O$/j dan kadar aliran udara lengai ialah 4.41 kgmol udara/j.*

[i] Calculate the composition of the treated air and used water.

*Kirakan komposisi udara yang telah dirawat dan air yang telah digunakan.*

[ii] Plot the operating lines (with intermediate points) on the x-y (mol fraction) equilibrium plot, and determine the number of theoretical trays needed.

*Plotkan garisan operasi (dengan titik perantaraan) pada plot keseimbangan x-y (pecahan mol), dan tentukan bilangan dulang teori yang diperlukan.*

Table Q.2.[a]. Equilibrium Data for Ammonia-Water System
*Jadual S.2.[a]. Data Keseimbangan bagi Sistem Ammonia- Air*

| Mole fraction of $NH_3$ in liquid, $x_A$ *Pecahan-mol $NH_3$ dalam cecair, $x_A$* | Mole fraction of $NH_3$ in vapor, *Pecahan-mol $NH_3$ dalam wap* $y_A$ (P = 1 atm) | |
|---|---|---|
| | 20°C | 30°C |
| 0 | 0 | 0 |
| 0.0126 | | 0.0151 |
| 0.0167 | | 0.0201 |
| 0.0208 | 0.0158 | 0.0254 |
| 0.0258 | 0.0197 | 0.0321 |
| 0.0309 | 0.0239 | 0.0390 |
| 0.0405 | 0.0328 | 0.0527 |
| 0.0503 | 0.0416 | 0.0671 |
| 0.0737 | 0.0657 | 0.105 |

*[18 marks/markah]*

[b] A packed tower is used to remove 90% of $NH_3$ from a 85.0 $m^3$/min feed gas containing 3 mole% of $NH_3$ and 97 mole% of air. Pure water at 293K and 1atm is used as absorbent. From the given information, estimating the required packed height. (Assume it is a dilute system).

*Suatu menara terpadat digunakan untuk menyingkirkan 90% $NH_3$ dari gas suapan 85.0 $m^3$/min yang mengandungi 3 mol% $NH_3$ dan 97 mol% udara. Air tulen pada 293 K dan 1 atm digunakan sebagai penyerap. Daripada maklumat yang diberi, anggarkan ketinggian padatan yang diperlukan. (Anggapkan ia adalah satu sistem yang cair).*

Packing = 1.5-inch Raschig rings
Henry's Law constant = 0.772 mole ratio $NH_3$ in air/mole ratio $NH_3$ in water
Mass flow rate of gas = 102.51kg/min
Mass flow rate of liquid = 66.22kg/min
$X_2$ = 0 (no recirculated liquid)
Mole ratio of $NH_3$ to $NH_3$ free gas entering the absorber = 0.03
Mole ratio of $NH_3$ to $NH_3$ free gas leaving the absorber = 0.003
Liquid mass velocity = 1500lbm/hr-ft$^2$
Gas mass velocity = 500 lbm/hr-ft$^2$

*Padatan = cincin Raschig 1.5 inci*
*Pemalar Hukum Henry = 0.772 nisbah mol $NH_3$ dalam udara / nisbah mol $NH_3$ dalam air*
*Kadar aliran jisim gas = 102.51 kg/min*
*Kadar aliran jisim cecair = 66.22 kg/min*
*$X_2$ = 0 (tiada cecair dikitar semula)*
*Nisbah mol $NH_3$ untuk gas bebas $NH_3$ memasuki penyerap = 0.03*
*Nisbah mol $NH_3$ untuk gas bebas $NH_3$ meninggalkan penyerap = 0.003*
*Halaju jisim cecair = 1500 lbm/hr-ft$^2$*
*Halaju jisim gas =500 lbm/hr-ft$^2$*

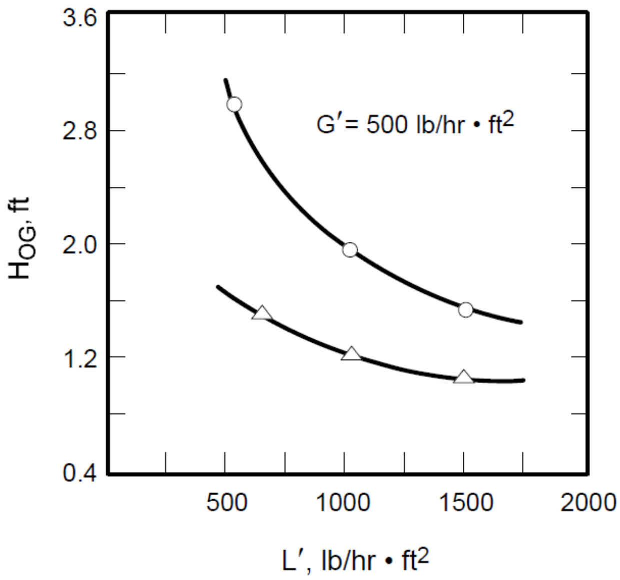


Figure Q.2.[b]. Height of a transfer unit for ammonia and water system.
*Rajah S.2.[b]. Ketinggian unit pemindahan untuk sistem amonia dan air.*

*[7 marks/markah]*

3. [a] Define the term "constant molar overflow" and show that for this condition the vapour and liquid flows in the upper section of a distillation column can be related by the equation:

*Takrifkan terma "limpahan molar malar" dan tunjukkan bahawa untuk keadaan ini wap dan cecair yang mengalir di dalam bahagian atas turus penyulingan boleh dihubungkan dengan persamaan:*

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1}$$

*[7 marks/markah]*

[b] A fractionation column is to separate 30 kg/h of a solution of benzene and toluene containing 0.6 mass fraction toluene into an overhead product containing 0.97 mass fraction benzene and a bottom product containing 0.98 mass fraction toluene. A reflux ratio of 3.5 is to be used and the feed is liquid at its boiling point. Compute the following, assuming a uniform pressure of 1 atm throughout the column:

*Suatu turus pemeringkatan akan memisahkan 30 kg/j larutan benzena dan toluena yang mengandungi 0.6 pecahan berat toluena kepada produk atas yang mengandungi 0.97 pecahan berat benzena dan produk bawah yang mengandungi 0.98 pecahan berat toluena. Pecahan refluks sebanyak 3.5 akan digunakan dan suapan ialah cecair pada titik didihnya. Kirakan yang berikut dengan mengandaikan tekanan seragam 1 atm di sepanjang turus:*

[i] Amount of distillate and bottom product
*Jumlah sulingan dan produk bawah*

[ii] Minimum number of theoretical trays at total reflux
*Bilangan minimum dulang teori pada refluks keseluruhan*

[iii] Minimum reflux ratio, $R_m$
*Pecahan refluks minimum*, $R_m$

[iv] Theoretical number of stages required
*Bilangan peringkat teori yang diperlukan*

[v] Optimal location of the feed
*Lokasi optimum suapan*

[vi] Actual number of trays if the tray efficiency is 0.80.
*Bilangan dulang sebenar jika kecekapan dulang ialah 0.80*

Table Q.3.[b].: Equilibrium data for benzene-toluene system
*Jadual S.3.[b]: Keseimbangan data untuk sistem benzena-toluena*

| *y* = Mole fraction of benzene in vapor<br>y = *Pecahan mol benzena dalam wap* | *x* = mole fraction of benzene in liquid<br>x = *Pecahan mol benzena dalam cecair* |
|---|---|
| 0.20 | 0.1 |
| 0.38 | 0.2 |
| 0.51 | 0.3 |
| 0.63 | 0.4 |
| 0.71 | 0.5 |
| 0.78 | 0.6 |
| 0.85 | 0.7 |
| 0.91 | 0.8 |
| 0.96 | 0.9 |
| 0.98 | 0.95 |

Molecular weight of benzene = 78 kg/kmol
*Berat molekul benzena = 78 kg/kmol*

Molecular weight of toluene = 92 kg/kmol
*Berat molekul toluena = 92 kg/kmol*

*[18 marks/markah]*

4. [a] Explain the differences between distillation and liquid-liquid extraction.
*Terangkan perbezaan antara penyulingan dan penyarian cecair-cecair.*
*[5 marks/markah]*

[b] Fresh halibut livers containing 25.7 wt% oil are to be extracted with pure ethyl ether to remove 95% of the oil in countercurrent multistage leaching process. The feed rate is 1000 kg of fresh livers per hour. The final exit overflow solution is to contain 70 wt % oil. The retention of solution by the inert solids (oil-free liver) of the liver varies as given in Table Q.4.[b].:

*Hati halibut segar yang mengandungi 25.7% berat minyak ingin disari dengan etil eter tulen untuk menyingkir 95% minyak dalam proses pengurasan berbilang-peringkat arus berlawanan. Kadar suapan ialah 1000 kg hati segar bagi setiap jam. Aliran keluar terakhir bagi larutan aliran atas mengandungi 70% berat minyak. Penahan larutan oleh pepejal lengai (hati bebas-minyak) bagi hati berubah-berubah seperti yang diberikan dalam Jadual S.4.[b]:*

Table Q.4.[b].
*Jadual S.4.[b].*

| N (kg inert solid/kg solution retained) *N (kg pepejal lengai/kg larutan yang tertahan)* | $y_A$ (kg oil/kg solution) $y_A$ *(kg minyak/kg larutan)* |
|---|---|
| 4.88 | 0.0 |
| 3.50 | 0.2 |
| 2.47 | 0.4 |
| 1.67 | 0.6 |
| 1.39 | 0.81 |

Calculate the amounts and compositions of the exit streams and the total number of theoretical stages.
*Kirakan jumlah dan komposisi aliran keluar dan jumlah bilangan peringkat teori.*
*[20 marks/markah]*

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Appendix

## Formulae and General Data

Atomic weights: H = 1, C = 12, N = 14, O = 16, S = 32, Cl = 35:5
Gas constant: R = 8.312 J/mol.K= 0.08206 L.atm/mol.K = 62.36 L.mmHg/mol.K
Pressure: 101324 Pa = 1 atm = 760 mm Hg
Acceleration due to gravity: g = 9.81 m/s$^2$
Properties of water (unless otherwise stated): $\rho$ = 1000 kg/m$^3$, $\mu$ = 1.00 mPa.s

**Diffusion**

*Fick's Law:*

$$J_A = -D_{AB}\frac{dc_A}{dz} \qquad J_A = -cD_{AB}\frac{dx_A}{dz} \qquad J_A = \left(-D_{AB}\cdot\frac{P_T}{RT}\right)\frac{dy_A}{dz}$$

*General equation for diffusion plus convection:*

$$N_A = -cD_{AB}\frac{dx_A}{dz} + \frac{c_A}{c}(N_A + N_B)$$

Equimolar counter diffusion:

$$J_A = \frac{D_{AB}c}{z_T}(x_{Ai} - x_A)$$

$$J_A = \frac{D_{AB}}{z_T}(c_{Ai} - c_A)$$

$$J_A = \frac{D_{AB}(p_{A1} - p_{A2})}{RT(z_2 - z_1)}$$

Unimolecular diffusion:

$$N_A = -cD_{AB}\frac{dx_A}{dz} + x_A N_A$$

$$N_A = \frac{D_{AB}c}{z_T}\ln\frac{1 - x_A}{1 - x_{Ai}}$$

$$N_A = \frac{D_{AB}P_T}{RT(z_2 - z_1)p_{BM}}(p_{A1} - p_{A2})$$

$$p_{BM} = \frac{p_{B2} - p_{B1}}{\ln(p_{B2}/p_{B1})}$$

$$N_A = \frac{D_{AB}\rho_M}{(z_2 - z_1)y_{BM}}(y_{A1} - y_{A2})$$

$$y_{BM} = \frac{y_{B2} - y_{B1}}{\ln(y_{B2}/y_{B1})}$$

*Molecular diffusion of solute in liquids:*

$$J_A = \frac{D_{AB} c_{av}}{z_T}(x_{Ai} - x_A) = \frac{D_{AB}}{z_T}(c_{Ai} - c_A)$$

$$N_A = \frac{D_{AB}}{(z_2 - z_1) x_{BM}} \left(\frac{\rho}{M}\right)_{av} (x_{A1} - x_{A2})$$

$$x_{BM} = \frac{x_{B2} - x_{B1}}{\ln(x_{B2} / x_{B1})}$$

*Film theory (bulk flow effect is not negligible):*

$$N_A = \frac{cD_{AB}}{\delta} \ln\left[\frac{1 - x_{A_b}}{1 - x_i}\right] = \frac{cD_{AB}}{\delta (1 - x_A)_{LM}} (x_{Ai} - x_{A_b})$$

$$(1 - x_A)_{LM} = (x_B)_{LM} = \frac{x_{A_i} - x_{A_b}}{\ln\left[(1 - x_{A_i})/(1 - x_{A_b})\right]}$$

*Mass transfer coefficients:*

Turbulent mass transfer with constant concentration:

$$J_{A1} = k_c'(c_{A1} - c_{A2})$$

$$k_c' = \frac{D_{AB} + \overline{\varepsilon_M}}{z_2 - z_1}$$

Turbulent mass transfer with equimolar counter diffusion:

$$N_A = k_c'(c_{A1} - c_{A2}) = k_G'(p_{A1} - p_{A2}) = k_y'(y_{A1} - y_{A2})$$

$$N_A = k_c'(c_{A1} - c_{A2}) = k_L'(c_{A1} - c_{A2}) = k_x'(x_{A1} - x_{A2})$$

Turbulent mass transfer with unimolecular diffusion:

$$N_A = \frac{k_c'}{x_{BM}}(c_{A1} - c_{A2}) = k_c(c_{A1} - c_{A2})$$

$$= \frac{k_x'}{x_{BM}}(x_{A1} - x_{A2}) = k_x(x_{A1} - x_{A2})$$

$$N_A = k_c(c_{A1} - c_{A2}) = k_G(p_{A1} - p_{A2}) = k_y(y_{A1} - y_{A2})$$

$$N_A = k_c(c_{A1} - c_{A2}) = k_L(c_{A1} - c_{A2}) = k_x(x_{A1} - x_{A2})$$

*Overall mass transfer:*

$$N_A = K_y(y_{A,G} - y_A^*)$$

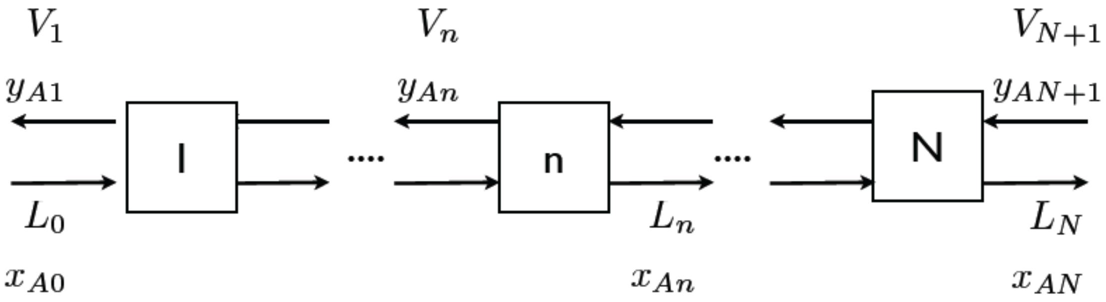
$$\frac{1}{K_y} = \frac{1}{k_y} + \frac{m'}{k_x}$$

$$N_A = K_x(x_A^* - x_{A,L})$$

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

**Absorption or Stripping**

*Stagewise contacting of totally immiscible phases:*




The subscript (A) is often omitted on the composition variables when no confusion is possible.

Equilibrium General: $y_{An} = f(x_{An})$

Gas-liquid (Henry's Law): $p_A = Hx_A$ or $y_A = H'x_A$

Liquid - liquid (Nernst): $y_A = mx_A$

Definitions of composition/flow variables:

$X_A = x_A/x_B$ $L_0 = Lx_B$ $V' = Vy_B$ B = inert componenet

For binary mixtures: $x_A + x_B = 1$

Operating line:

$$y_{An+1} = \left(\frac{L_n}{V_{n+1}}\right) x_{An} + \left(\frac{V_1 y_{A1} - L_0 x_{A0}}{V_{N+1}}\right)$$

$$\left(\frac{y_{An+1}}{1 - y_{An+1}}\right) = \left(\frac{L'}{V'}\right)\left(\frac{x_{An}}{1 - x_{An}}\right) + \left(\frac{y_{A1}}{1 - y_{A1}}\right) - \left(\frac{L'}{V'}\right)\left(\frac{x_{A0}}{1 - x_{A0}}\right)$$

$$Y_{An+1} = \left(\frac{L'}{V'}\right) X_{An} + Y_{A1} - \left(\frac{L'}{V'}\right) X_{A0}$$

Absorption factor: L/mV

*Design of absorber:*

Transfer from V to L (Absorption):

$$\frac{y_{AN+1} - y_{A1}}{y_{AN+1} - mx_0} = \frac{A^{N+1} - A}{A^{N+1} - 1}$$

$$N = \frac{\log\left(\frac{y_{AN+1} - mx_{A0}}{y_{A1} - mx_{A0}}\left(1 - \frac{1}{A}\right) + \frac{1}{A}\right)}{\log A}$$

When A = 1

$$N = \frac{y_{AN+1} - y_{A1}}{y_{A1} - mx_{A0}}$$

Transfer from L to V (Stripping):

$$\frac{x_{A0} - x_{AN}}{x_{A0} - y_{AN+1}/m} = \frac{(1/A)^{N+1} - (1/A)}{(1/A)^{N+1} - 1}$$

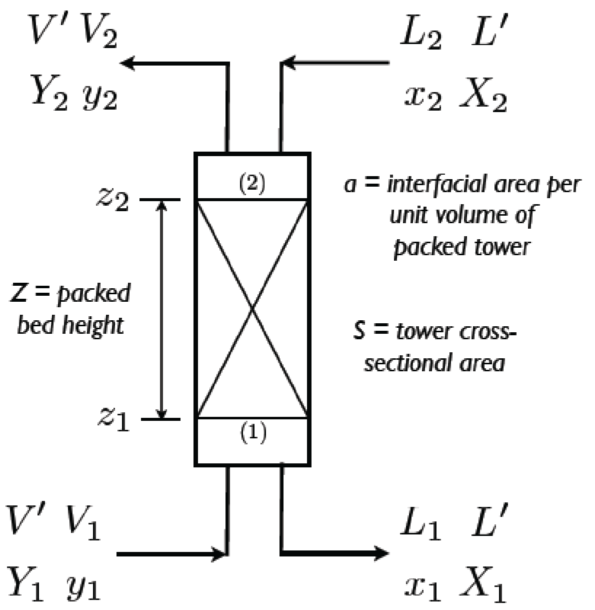
$$N = \frac{\log\left[\left(\frac{x_{A0} - y_{AN+1}/m}{x_{AN} - y_{AN+1}/m}\right)(1 - A) + A\right]}{\log(1/A)}$$

When A = 1

$$N = \frac{x_{A0} - x_{AN}}{x_{AN} - y_{AN+1}/m}$$

$$C_S = u_o\sqrt{\frac{\rho_y}{\rho_x - \rho_y}}$$

$$\text{HETP} = \frac{l_T}{N_t}$$




General:

$$Z = \int_{y_1}^{y_2} \frac{V}{NaS} \cdot \frac{(-dy)}{(1-y)} = \int_{x_1}^{x_2} \frac{L}{NaS} \cdot \frac{(-dx)}{(1-x)}$$

Manipulation of the above:

$$Z = \int_{y_1}^{y_2} \frac{V}{K_y aS} \cdot \frac{(-dy)}{(1-y)(y-y^*)} = \int_{y_1}^{y_2} \frac{V}{K_y' aS} \cdot \frac{(1-y)_{*LM}}{(1-y)} \frac{(-dy)}{(y-y^*)}$$

Dilute solutions:

$$\frac{(1-y)_{*LM}}{(1-y)} \approx 1.0$$

$$Z \approx \left(\frac{V_{\text{ave}}}{K_y' aS}\right) \int_{y1}^{y2} \frac{(-dy)}{(y-y^*)}$$

Additionally – Henry's Law holds

$$\begin{aligned} Z &= \left(\frac{V_{\text{ave}}}{K_y' aS}\right)(-1)\left(\frac{(y_2-y_1)}{(y-y^*)}\right)_{\text{Log Mean } 1\to 2} \\ &\equiv H_{oy}N_{oy} \end{aligned}$$

Analogous equations for gas film basis, and for liquid-phase balance

$$\begin{aligned} Z &= H_y N_y = H_G N_G = H_{oy} N_{oy} = H_{oG} N_{oG} \\ &= H_x N_x = H_L N_L = H_{ox} N_{ox} = H_{oL} N_{oL} \end{aligned}$$

$$Z = HETP \times N$$

Chilton and Colburn equations:

$$H_{OG} = \frac{V_{ave}}{K_y aS}$$

$$N_{OG} = \frac{\ln\{[(A-1)/A][(y_{in} - Kx_{in})/(y_{out} - Kx_{in})] + (1/A)\}}{(A-1)/A}$$