Ex Problem 10 - Countercurrent Packed Tower for Absorption of Ammonia Gas (Pilat)

Given

Gas (air flow) upward of 4,000 acfm at 68F or 528R and 1 atm pressure
Inlet gaseous conc. of 6,000 ppm NH_3 (dry basis) $Y_{in} = 0.006$
Inlet water conc of 0.0006 mole fraction NH_3 in water $x_{in}= 0.0006$
Liquid flow rate = 500 lb liquid/ ft^2 hr Mol Wt $H_2O = M_L$=18.016 lb/lbmole
Gaseous flow rate of 500 lb gas (air) / ft^2 hr Mol Wt Gas (air) = 29 lb/lbmole
atomic wt N = 14.0067 atomic wt H = 1.0079
Assume Govt Emission Std is 1,000ppm NH_3 (dry basis) so $y_{out} = 0.001$

Find

a) H = Henry's law constant from solubility data of NH_3 in water at 20°C
b) H_{OG} from ammonia-water data of Fellinger for 1.5" Raschig ring packing
c) Liquid molar flow rate L_m (lb moles/ft^2 hr)
d) Gaseous molar flow rate G_m (lb moles/ft^2 hr)
e) X_{out} via Mass Balance around the absorption tower
f) Number of gas phase mass transfer units N_{OG}
g) Height of packed section in tower Z = (H_{OG}) (N_{OG}) h) Tower Diameter (ft)
i) Gas phase overall mass transfer coefficient K_Ga (lb moles/ft^3 hr atm)
j) Gas velocity in tower (ft/sec)
k) Gas residence time in packed section of tower (seconds)
L) L/G = Liquid/Gas flow rate ratio in gallons water / ft^3 1000 gas
m) Draw Y-X graph with equilibrium curve and tower operating line.
n) Ammonia collection efficiency

Need to define unit lbmole

$$\mathrm{lbmole} := (\mathrm{mole})\cdot(453.6)$$

$$M_L := \frac{18.016\cdot \mathrm{lb}}{\mathrm{lbmole}}$$

$$M_{NH3} := \frac{17.031\cdot \mathrm{lb}}{\mathrm{lbmole}}$$

$$M_G := 29\cdot\frac{\mathrm{lb}}{\mathrm{lbmole}}$$

$Y_{out} := 0.001$ $X_{in} := 0.0006$

$Y_{in} := 0.006$ Xout = Unknown

$$Q_{Gas} := 4000\cdot ft^3\cdot min^{-1}$$

$Ptotal := 1\cdot atm$ $P := 1\cdot atm$

$T := 528\cdot R$ $$mmHg := \frac{atm}{760}$$

a) Calc Henry's law constant H using equilibrium solubility data for NH_3 in water at temperatures in 20°C range from Table B-4 page 682 Cooper & Alley (3rd Ed)

Six NH_3 vapor pressures

$i := 0 .. 5$

(lb NH_3 per 100 lb H2O	NH_3 Partial Pressure (mm Hg)
2	12.0
3	18.2
4	24.9
5	31.7
7.5	50.0
10	69.6

$$WtNH3 := \begin{pmatrix}2\\3\\4\\5\\7.5\\10\end{pmatrix}\cdot lb \qquad PNH3 := \begin{pmatrix}12.0\\18.2\\24.9\\31.7\\50.0\\69.6\end{pmatrix}\cdot mmHg \qquad PNH3 = \begin{pmatrix}12\\18.2\\24.9\\31.7\\50\\69.6\end{pmatrix} torr$$

Mole fraction NH_3 in liquid phase = X_{NH3}
Mole fraction NH_3 in gas phase = Y_{NH3}
Henry's Law Constant = H

$$xNH3 := \frac{molesNH3inWater}{TotalMolesinWater}$$

$$yNH3_i := \frac{PNH3_i}{Ptotal}$$

$$X_{NH3_i} := \frac{\dfrac{WtNH3_i}{\dfrac{17.031\cdot lb}{lbmole}}}{\dfrac{WtNH3_i}{\dfrac{17.031\cdot lb}{lbmole}} + \dfrac{100\cdot lb}{\dfrac{18.016\cdot lb}{lbmole}}}$$

$$H_i := \frac{yNH3_i}{X_{NH3_i}}$$

$$y_{NH3} = \begin{pmatrix}0.016\\0.024\\0.033\\0.042\\0.066\\0.092\end{pmatrix} \qquad X_{NH3} = \begin{pmatrix}0.021\\0.031\\0.041\\0.05\\0.074\\0.096\end{pmatrix} \qquad H = \begin{pmatrix}0.7621\\0.7786\\0.8071\\0.8303\\0.895\\0.9573\end{pmatrix}$$

Assume H = 0.7614 = y_{NH3}/X_{NH3} because the inlet liquid phase NH_3 concentration X_{in} is low at 0.0006

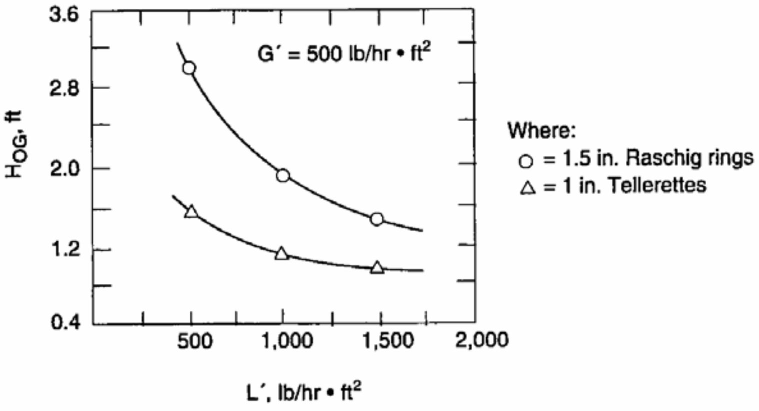
Henrys law constant H is in units of
(mole fraction NH_3 in gas phase) / (mole fraction NH_3 in liquid phase)

(a) $H := 0.7614$

b) Obtain height of gas phase mass transfer unit H_{OG} = 3.0 ft from graph (shown below)
for 1.5" Raschig rings, L = 500 lb liquid / ft^2 hr, G = 500 lb air / ft^2 hr. pp 456 Noll

(b) $H_{OG} := 3.0 \cdot ft$

Figure 12.9
Column Packing Comparison for Ammonia and Water System



Source: Leva 1951

c) Liquid flow rate in lbmole units = L_m
Liquid flow rate in lb units = L

$L := 500 \cdot lb \cdot ft^{-2} \cdot hr^{-1}$

$M_L = 18.016\, gm \cdot mole^{-1}$

$L_m := \dfrac{L}{M_L}$

d) Gaseous molar flow rate = Gm
Gaseous mass flow rate = G

(c) $L_m = 27.753 \dfrac{lbmole}{ft^2 \cdot hr}$

$M_G = 29\, gm \cdot mole^{-1}$

$G := 500 \cdot lb \cdot ft^{-2} \cdot hr^{-1}$

$Y_{in} = 0.006$ $Y_{out} = 0.001$ $X_{in} = 0.0006$

$G_m := \dfrac{G}{M_G}$

(d) $G_m = 17.241 \dfrac{lbmole}{ft^2 \cdot hr}$

e) The mass balance equation
NH_3 into tower = NH_3 out of tower
Y_{in} Gm +X_{in} Lm = Y_{out} Gm + X_{out} Lm
Xin was given as 0.0006 to can solve for the unknown X_{out}

$X_{in} = 0.0006$

$Xout := \left(\dfrac{G_m}{L_m}\right) \cdot (Y_{in} - Y_{out}) + X_{in}$

$H = 0.7614$

(e) $Xout = 0.003706$

$$Xout2 := \left[\dfrac{17.241 \cdot \dfrac{lbmole}{ft^2 \cdot hr}}{27.753 \cdot \dfrac{lbmole}{ft^2 \cdot hr}}\right] \cdot (.006 - .001) + .0006$$

$Xout2 = 0.003706$

Note that liquid conc X_{out} = 0.003706 is in *mole fraction units*,
***not ppm* (in liquids, ppm means parts per million by weight whereas in gases, ppm means ppm by mole or by gaseous volume)**

To graph the operating line using the liquid phase concentration X as the X axis variable we will need a linear equation relating the tower gas phase NH_3 conc Y in terms of the liquid phase NH_3 conc X.
Starting at Xin = 0.0006 at the top of the tower and increasing X to Xout one can obtain the linear operating equation for Y. Note that this equation represents the actual gas phase and liquid phase conc in the absorption tower (one could take a sample of the tower gases & liquids & measure the NH_3 conc).

Operating line linear equation ▪ →

$Y := \left(\dfrac{L_m}{G_m}\right) \cdot (X - X_{in}) + Y_{out}$

f.) Number of Gas Phase Mass Transfer Units or N_{OG}

$Ptotal = 1\,atm$

Because it is difficult to put an asterisk to denote the equilibrium conc for Y or Y* in Mathcad, let Y_{starin} be the gas phase mole fraction conc of NH_3 in equilibrium with the liquid water at the gaseous inlet (bottom of this tower) and let $Y_{starout}$ be the gas phase conc. of NH_3 in equilibrium with the liquid water at the gaseous outlet (top of tower). Using nomenclature of Y_{in}, Y_{out}, X_{in}, X_{out}, $Ystar_{in}$, and $Ystar_{out}$ should help to reduce confusion as to where these concentrations occur and make it easier to label diagrams and tower illustrations.

$Ystar_{in} := (H)\cdot Xout$

$Ystar_{in} = 0.00282$

$Ystar_{out} := H\cdot X_{in}$

$Ystar_{out} = 0.00046$

$$N_{OG} := \left[\left[\frac{Y_{in} - Y_{out}}{\left(Y_{in} - Ystar_{in}\right) - \left(Y_{out} - Ystar_{out}\right)}\right]\cdot \ln\left(\frac{Y_{in} - Ystar_{in}}{Y_{out} - Ystar_{out}}\right)\right]$$

(f) $N_{OG} = 3.352$

there are 3.352 gas phase mass transfer units

Note that the above equation for N_{OG} assumes a straight equilibrium line and a straight operating line (which is an OK assumption for the absorption of dilute gas concentrations and air pollutants are usually in the dilute concentration range).

g.) Height of Packed Tower Section = Z = HOG NOG

$Z := H_{OG}\cdot N_{OG}$

$Z = 10.057\,ft$

(g)

h) Tower Diameter

$Z_2 := (3.0\cdot ft)\cdot(3.352)$

$Z_2 = 10.056\,ft$

$RG := 0.082054\cdot\frac{liter\cdot atm}{mole\cdot K}$

$Mg := \frac{29\cdot gm}{mole}$

The height of the 1.5 inch Raschig ring packed section in the absorption tower = 10.057 ft

$G = 500\frac{lb}{ft^2\cdot hr}$

$\rho_g := \frac{P\cdot Mg}{RG\cdot T}$

$T = 528\,R$

$P := 1\cdot atm$

$Area := \frac{Q_{Gas}\cdot \rho_g}{G}$

Area = tower cross-sectional area

gas density = ρ_g

$\rho_g = 0.075217\,lb\cdot ft^{-3}$

$$Area := \left(\frac{4000\cdot ft^3\cdot min^{-1}}{500\cdot\frac{lb}{ft^2\cdot hr}}\right)\cdot\left(0.07522\cdot\frac{lb}{ft^3}\right)$$

$Area = 36.106\,ft^2$

$$Diameter := \left(\frac{Area\cdot 4}{\pi}\right)^{0.5}$$

$Diameter = 6.78\,ft$

(h)

Tower Diameter = 6.78 ft

i) Gas Phase Overall Mass Transfer Coefficient K_Ga

$G_m = 17.241\,lbmole\cdot ft^{-2}\cdot hr^{-1}$

Graphs of the *measured* K_Ga versus liquid or gas flow rates are provided by equipment manufacturers for various absorption packing types and sizes.

$$KGA := \frac{\left(17.241\cdot\frac{lbmole}{ft\cdot hr}\right)}{(3\cdot ft)\cdot(1\cdot atm)}$$

$H_{OG} = 3\,ft$

$P = 1\,atm$

$KGA := \frac{G_m}{H_{OG}\cdot P}$

(i)

$KGA = 1.752\,m\frac{lbmole}{ft^3\cdot hr\cdot atm}$

j) Gas Velocity (superficial) in packed tower

$Velocity := \left(Q_{Gas}\right)\cdot\left(Area^{-1}\right)$

$Vel_2 := \left(4000\cdot ft^3\cdot min^{-1}\right)\cdot\left(36.106\cdot ft^2\right)^{-1}$

$Vel_2 = 1.846\,ft\cdot sec^{-1}$

(j)

$Velocity = 1.846\,ft\cdot sec^{-1}$

k) Gas Residence time in packed absorption tower section

$ResidenceTime := Z\cdot\left(Velocity^{-1}\right)$

$ResidenceTime_2 := (10.056\cdot ft)\cdot\left(1.846\cdot ft\cdot sec^{-1}\right)^{-1}$

(k)

$ResidenceTime = 5.447\,sec$

$ResidenceTime_2 = 5.447\,sec$

L) Liquid to gas flow rate ratio L/G in gallons/1000 cf gas

L/G = 9.019 gallons water per 1000 ft^3 gas

$LG = 9.019 \frac{gal}{1000 \cdot ft^3}$

$LG := \frac{L \cdot \left(8.34 \cdot \frac{lb}{gal}\right)^{-1}}{G \cdot \rho_g^{-1}}$

(l)

m) Graph of Y-X equilibrium curve and Mass Balance Operating Line

$j := 0 .. 7$

$X := \begin{pmatrix} .0005 \\ .0006 \\ .001 \\ .002 \\ .0025 \\ .0030 \\ .0035 \\ .003706 \end{pmatrix}$

Ystar = Gas phase equilibrium NH_3 conc in mole fraction units

The 8 X values shown in the matrix to the right are for the horizontal axis in the graph and span the range from X_{in} to X_{out}

$Y_{out} = 0.001$

$X_{in} = 0.0006$

$Y_{in} = 0.006$

$Xout = 0.003706$

Now to put the operating line equation on an Y-X graph

$OpSlope := \frac{L_m}{G_m}$

$H = 0.761$

$Ystar_j := H \cdot (X_j)$

$YY_j := OpSlope \cdot X_j$

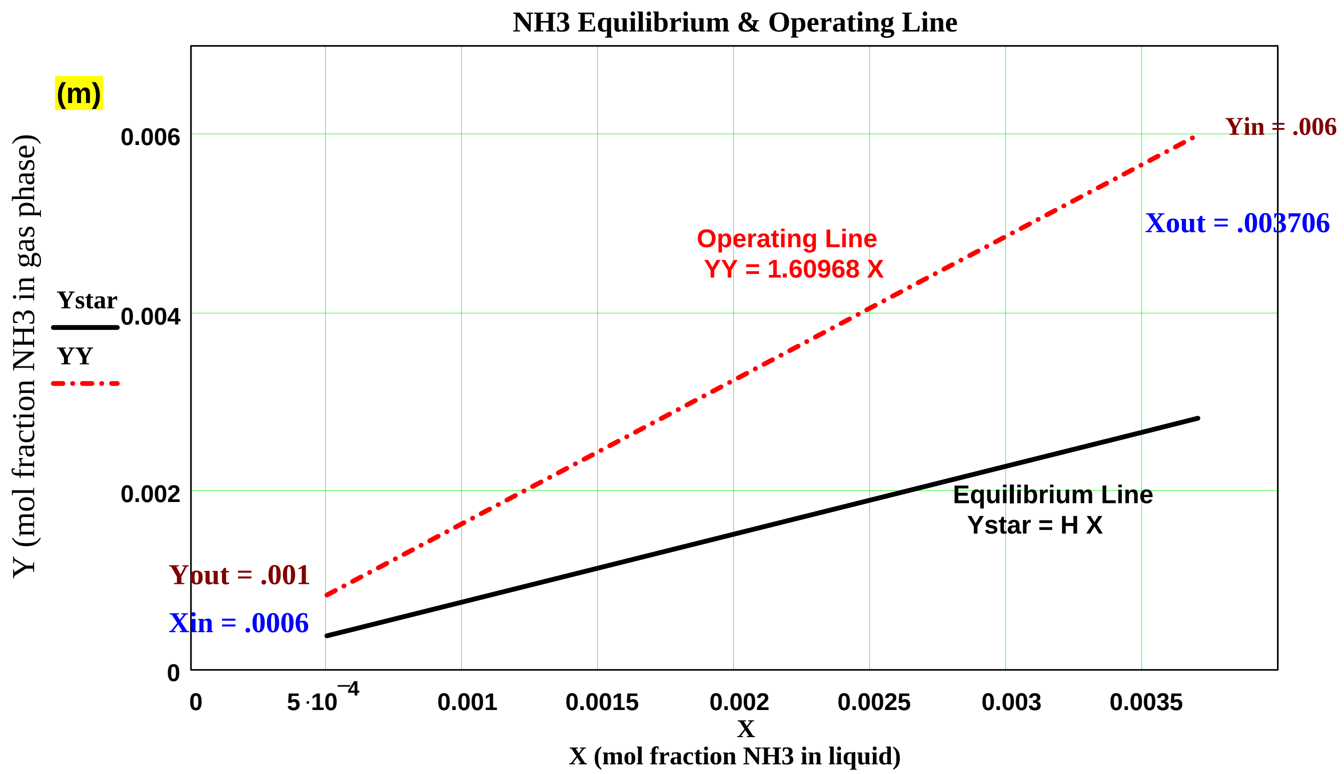
$OpSlope = 1.6096803$

$YY_j := (OpSlope) \cdot (X_j - X_{in}) + Y_{out}$

$YY_7 = 0.006$

$X_7 = 0.003706$

The operating line equation YY = 1.60968 X is upper dash-dot line shown in below graph. The difference between the operating line & the lower solid equilibrium equation Ystar = H X line shows the NH_3 concentration gradient driving force; the concentration gradient (y-y*) causes the NH_3 to move from the gas into the liquid.



$Y_{in} = 0.006$

$X_{out} = 0.003706$

$Y_{out} = 0.001$

$X_{in} = 0.0006$

Govt Emission Std is 1,000ppm NH_3 (dry basis) so Yout = 0.001

Remember, the operating line represents the *actual* concentrations of NH_3 in the gas and liquid inside the tower and thus these are *measurable* parameters. Y_{out} and X_{in} are at the top of the tower and Y_{in} and X_{out} are at the bottom of the tower for countercurrent flow (see illustration on next page)

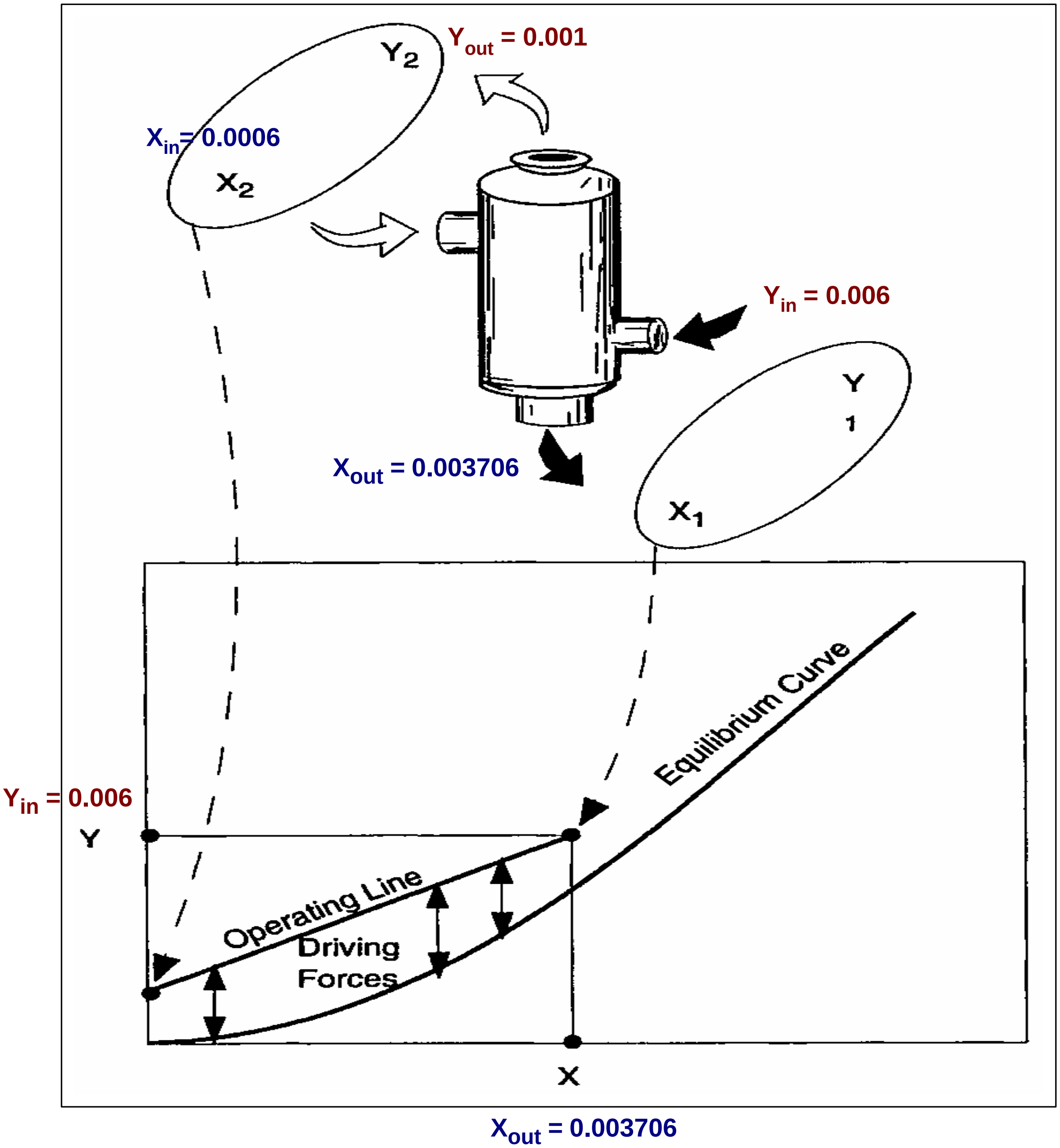
n) Ammonia collection efficiency

$$\mathrm{PercentCollectionEff} := \frac{(Y_{in} - Y_{out}) \cdot 100}{Y_{in}}$$

$\mathrm{PercentCollectionEff} = 83.333$

(n)

Illustration below shows the ammonia absorption inlet and outlet concentrations for a countercurrent absorption tower.



Y = gas phase pollutant concentrations (mole fraction)

X = liquid phase pollutant concentrations (mole fraction)

Pilat Comment:
I prefer to use Y_{in}, Y_{out}, X_{in}, and X_{out} rather than Y_1, Y_2, X_1, and X_2 because I think it is too easy to forget whether the subscripts 2 and 1 indicate the top or bottom of an absorption tower.