

Countercurrent Packed Tower for Absorption of Ammonia Gas

Given

Gas (air flow) upward of 4,000 acfm at 68F or 528R and 1 atm pressure
 Inlet gaseous conc. of 6,000 ppm NH₃ (dry basis) $Y_{in} = 0.006$
 Inlet water conc of 0.0006 mole fraction NH₃ in water $x_{in} = 0.0006$
 Liquid flow rate = 500 lb liquid/ ft² hr Mol Wt H₂O = ML=18 lb/lbmole
 Gaseous flow rate of 500 lb gas (air) / ft² 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 NH₃ (dry basis) so $y_{out} = 0.001$

Find

- H = Henry's law constant from solubility data of NH₃ in water at 20°C
- H_{OG} from ammonia-water data of Fellinger for 1.5" Raschig ring packing
- Liquid molar flow rate Lm (lb moles/ft² hr)
- Gaseous molar flow rate Gm (lb moles/ft² hr)
- X_{out} via Mass Balance around the absorption tower
- Number of gas phase mass transfer units N_{OG}
- Height of packed section in tower Z = (H_{OG}) (N_{OG}) h) Tower Diameter (ft)
- Gas phase overall mass transfer coefficient K_{Ga} (lb moles/ft³ hr atm)
- Gas velocity in tower (ft/sec)
- Gas residence time in packed section of tower (seconds)
- L/G = Liquid/Gas flow rate ratio in gallons water / ft³ 1000 gas
- Draw Y-X graph with equilibrium curve and tower operating line.
- Ammonia collection efficiency

Need to define unit lbmole

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

$$ML := \frac{18.016 \cdot \text{lb}}{\text{lbmole}}$$

$$M_{NH3} := \frac{17.030 \cdot \text{lb}}{\text{lbmole}}$$

$$MG := 29 \cdot \frac{\text{lb}}{\text{lbmole}}$$

$$Y_{in} := 0.006$$

$$X_{in} := 0.0006$$

$$Y_{out} := 0.001$$

$$X_{out} = \text{Unknown}$$

$$P_{total} := 1 \cdot \text{atm}$$

$$T := 528 \cdot R$$

$$\text{mmHg} := \frac{\text{atm}}{760}$$

$$i := 0..5$$

- Calc Henry's law constant H using equilibrium solubility data for NH₃ in water at temperatures in 20°C range from Table B-4 page 682 Cooper & Alley (3rd Ed)

(lb NH ₃ per 100 lb H ₂ O)	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

$$Wt_{NH3} := \begin{pmatrix} 2 \\ 3 \\ 4 \\ 5 \\ 7.5 \\ 10 \end{pmatrix} \cdot \text{lb}$$

$$P_{NH3} := \begin{pmatrix} 12.0 \\ 18.2 \\ 24.9 \\ 31.7 \\ 50.0 \\ 69.6 \end{pmatrix} \cdot \text{mmHg}$$

$$P_{NH3} = \begin{pmatrix} 12 \\ 18.2 \\ 24.9 \\ 31.7 \\ 50 \\ 69.6 \end{pmatrix} \text{ torr}$$

Mole fraction NH₃ in liquid = X_{NH3}

Mole fraction NH₃ in gas phase = Y_{NH3}

Henry's Law Constant = H

$$y_{NH3} = \begin{pmatrix} 0.016 \\ 0.024 \\ 0.033 \\ 0.042 \\ 0.066 \\ 0.092 \end{pmatrix}$$

$$X_{NH3} = \begin{pmatrix} 0.021 \\ 0.031 \\ 0.041 \\ 0.05 \\ 0.074 \\ 0.096 \end{pmatrix}$$

$$H = \begin{pmatrix} 0.7614 \\ 0.7778 \\ 0.8063 \\ 0.8296 \\ 0.8942 \\ 0.9565 \end{pmatrix}$$

$$x_{NH3} := \frac{\text{molesNH3inWater}}{\text{TotalMolesinWater}}$$

$$\frac{Wt_{NH3}_i}{17 \cdot \text{lb}} \cdot \frac{1}{\text{lbmole}}$$

$$y_{NH3}_i := \frac{P_{NH3}_i}{P_{total}}$$

$$X_{NH3}_i := \frac{Wt_{NH3}_i}{\frac{17 \cdot \text{lb}}{\text{lbmole}} + \frac{100 \cdot \text{lb}}{\text{lbmole}}}$$

$$H_i := \frac{y_{NH3}_i}{X_{NH3}_i}$$

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

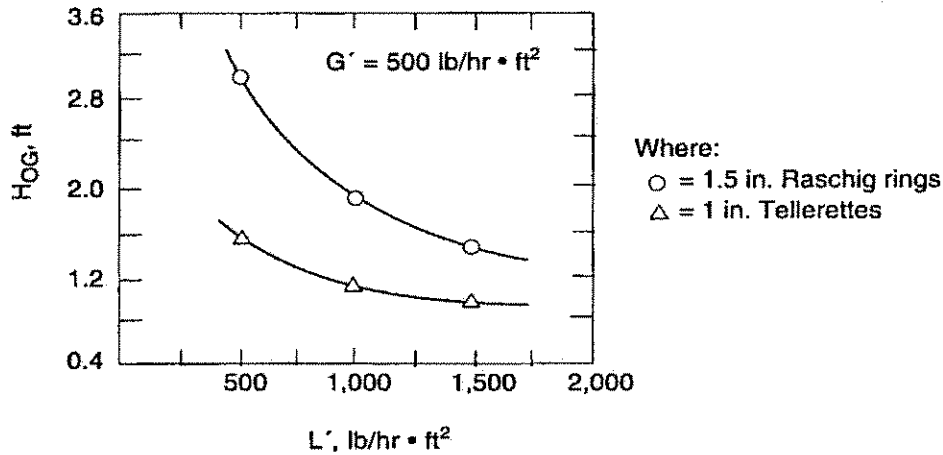
Henry's law constant H is in units of
 (mole fraction NH₃ in gas phase) / (mole fraction NH₃ in liquid phase)

$$(a) \quad H := 0.7614$$

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) $H_{OG} := 3.0$ 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

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

$$ML = 18.016 \text{ gm} \cdot \text{mole}^{-1}$$

$$ML = 18.016 \text{ lb} \cdot \text{lbmole}^{-1}$$

$$L_m := \frac{L}{ML}$$

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

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

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

$$G_m := \frac{G}{MG}$$

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

$$MG = 29 \text{ gm} \cdot \text{mole}^{-1}$$

$$MG = 29 \text{ lb} \cdot \text{lbmole}^{-1}$$

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

$$X_{in} = 0.0006$$

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

$$H = 0.7614$$

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)

(e) $X_{out} = 0.003706$

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 concentration Y in terms of the liquid phase concentration X . Starting at $X_{in} = 0.0006$ at the top of the tower and increasing X to X_{out} 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 and measure the concentrations).

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

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

Because it is difficult to put an asterisk to denote the equilibrium conc for Y or Y* in Mathcad, let Ystarin 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 Ystarout 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} , Y_{starin} , and $Y_{starout}$ should help to reduce confusion as to where these concentrations occur and make it easier to label diagrams and tower illustrations.

$$NOG := \left[\frac{Y_{in} - Y_{out}}{(Y_{in} - Y_{starin}) - (Y_{out} - Y_{starout})} \right] \cdot \ln \left(\frac{Y_{in} - Y_{starin}}{Y_{out} - Y_{starout}} \right)$$

(f) $NOG = 3.352$ there are 3.352 gas phase mass transfer units.

$P_{total} = 1 \text{ atm}$

out

$Y_{starin} := (H) \cdot X_{out}$

$Y_{starin} = 0.00282$

$Y_{starout} := H \cdot X_{in}$

$Y_{starout} = 0.00046$

Note that the above equation for NOG 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

$Z := HOG \cdot NOG$

$Z = 10.057 \text{ ft}$ **(g)**

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

h) Tower Diameter

$T = 528 \text{ R}$ $P := 1 \cdot \text{atm}$

$Mg := \frac{29 \cdot \text{gm}}{\text{mole}}$ $RG := 0.082054 \cdot \frac{\text{liter} \cdot \text{atm}}{\text{mole} \cdot \text{K}}$

gas density = ρ_g

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

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

$\text{Area} := \left(\frac{4000 \cdot \text{ft}^3 \cdot \text{min}^{-1}}{G} \right) \cdot (\rho_g)$

$\text{Area} = 36.104 \text{ ft}^2$

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

$\text{Diameter} = 6.78 \text{ ft}$

(h)

Tower Diameter = 6.78 ft

i) Gas Phase Overall Mass Transfer Coefficient K_{Ga}

Graphs of the *measured* K_{Ga} versus liquid or gas flow rates are provided by equipment manufacturers for various packing types and sizes

$KGA := \frac{G_m}{HOG \cdot P}$ $G_m = 17.241 \text{ lbmole} \cdot \text{ft}^{-2} \cdot \text{hr}^{-1}$
 $HOG = 3 \text{ ft}$ $P = 1 \text{ atm}$

$KGA = 5.747 \frac{\text{lbmole}}{\text{ft}^3 \cdot \text{hr} \cdot \text{atm}}$ **(i)**

j) Gas Velocity (superficial) in packed tower

$\text{Velocity} := (4000 \cdot \text{ft}^3 \cdot \text{min}^{-1}) \cdot (\text{Area}^{-1})$

$\text{Velocity} = 1.847 \text{ ft} \cdot \text{sec}^{-1}$

(j)

Gas Velocity = 1.857 ft/sec

k) Gas Residence time in packed absorption tower section

$\text{ResidenceTime} = 5.446 \text{ sec}$

(k)

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

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

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

$LG = 9.019 \frac{\text{gal}}{1000 \cdot \text{ft}^3}$ **(l)**

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

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

$j := 0..7$

Ystar = Gas phase equilibrium NH₃ conc
in mole fraction units

Y_{out} = 0.001 X_{in} = 0.0006
Y_{in} = 0.006 X_{out} = 0.003706

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}

X :=

- .0005
- .0006
- .001
- .002
- .0025
- .0030
- .0035
- .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 · (X_j)

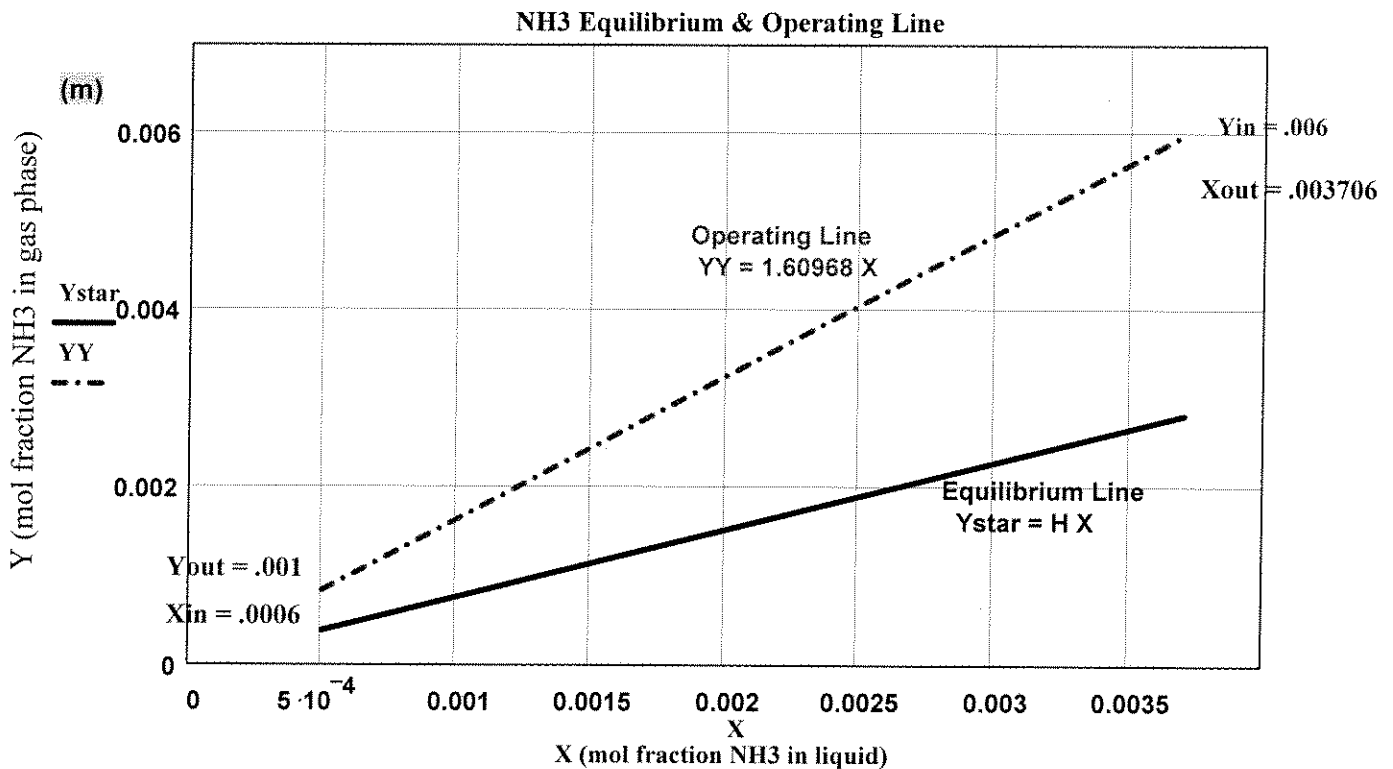
YY_j := OpSlope · X_j OpSlope = 1.6096803

YY_j := (OpSlope) · (X_j - X_{in}) + Y_{out}

YY₇ = 0.006

X₇ = 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 NH₃ concentration gradient driving force; the concentration gradient (y-y*) causes the NH₃ to move from the gas into the liquid.



Y_{in} = 0.006 X_{out} = 0.003706

Govt Emission Std is 1,000ppm NH₃ (dry basis) so Y_{out} = 0.001

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

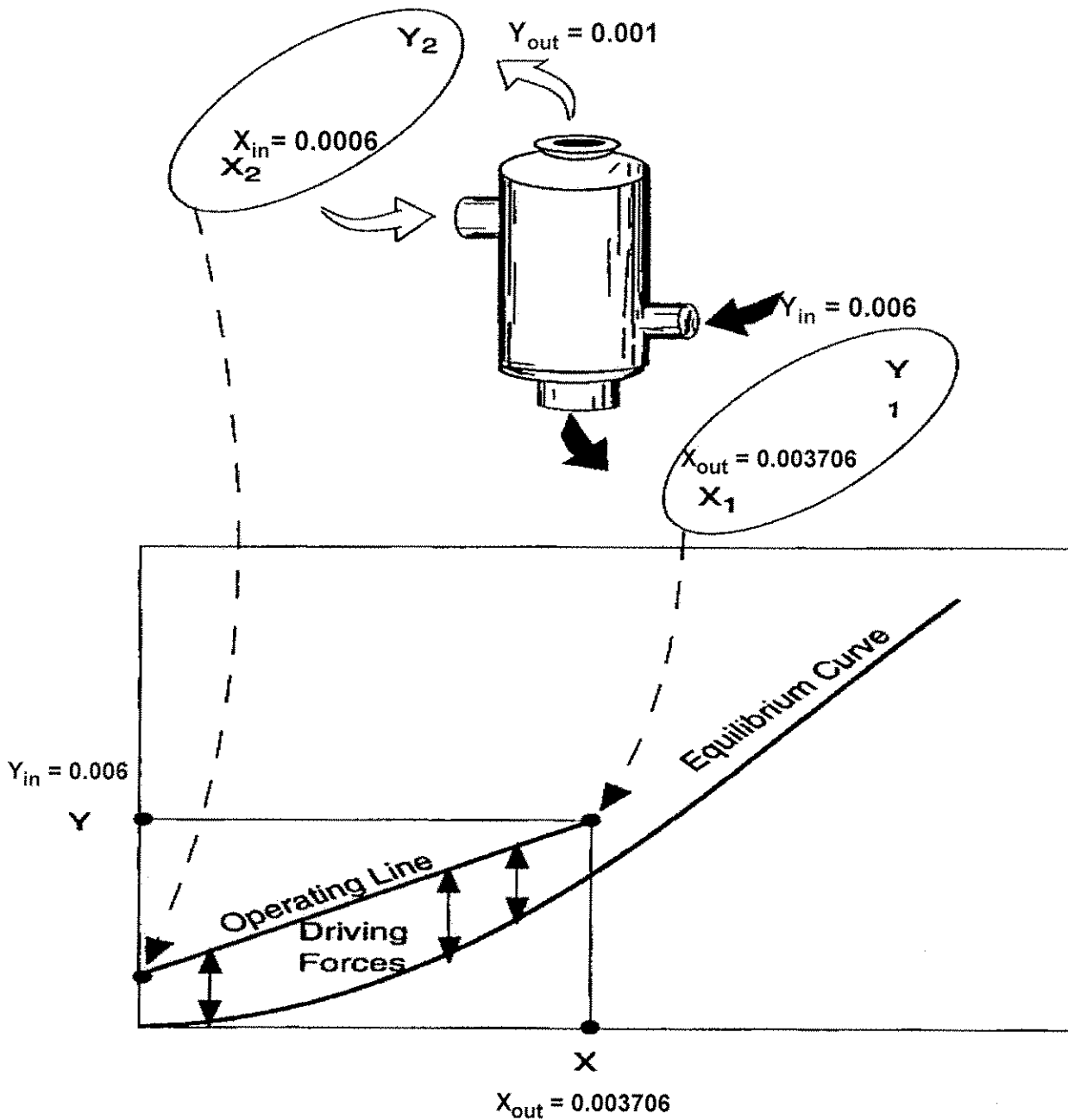
Remember, the operating line represents the *actual* concentrations of NH₃ in the gas and liquid inside the tower and thus these are *measurable* parameters. Y_{out} and X_{in} are at the top of the tower and Y_{in} and X_{out} are at the bottom of the tower for countercurrent flow (see illustration on next page)

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

CollectionEff = 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.