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#### A01: Gas-Liquid Processes

#### Note:

- 1. No need to redo all the calculations.
- Check which parameters are critical for certain values (rough sensitivity analysis) and see if there could be downstream effects in the calculations.
- Show only those calculations that are necessary to change the designs in the six examples or to be able to answers pertinent questions asked.

# The pilot plant data in Example 6.1 in the AWWA handbook are actually based on an air:water ratio of 1000:1, but calculations are performed, incorrectly, on a 100:1 ratio. What would the effect be on the K<sub>1</sub> a value if calculated on a 1000:1 ratio?

Stategy: follow the solution provided, but change the V/Q ratio to 1000 instead of 100.

1. Use the Henry's law constant from T 6-2 & calculate the stripping factor A:W ratio of 1000.

$$\mathbf{H} \coloneqq 0.0177 \qquad \left[\frac{\mathbf{V}}{\mathbf{Q}}\right] \coloneqq 1000$$
$$\mathbf{R}_1 \coloneqq \left[\frac{\mathbf{V}}{\mathbf{Q}}\right] \cdot \mathbf{H} = 17.7$$

For each sample port depth and MTBE conc, calculate the NTU using Eq 6-35.

$$C_{0} \coloneqq 125 \frac{\mu g}{L} \qquad C_{e} \coloneqq \begin{pmatrix} 66.3\\ 48.5\\ 34.5\\ 25.7 \end{pmatrix} \frac{\mu g}{L} \qquad \text{Depth} \coloneqq \begin{pmatrix} 0.76\\ 1.52\\ 2.29\\ 3.05 \end{pmatrix} m$$
$$\text{NTU} \coloneqq \frac{R_{1}}{R_{1} - 1} \cdot \ln \left[ \frac{\frac{C_{0}}{C_{e}} (R_{1} - 1) + 1}{R_{1}} \right] = \begin{pmatrix} 0.644\\ 0.966\\ 1.32\\ 1.628 \end{pmatrix}$$

Plot the NTU as a function of the column depth and find regression line.



Determine HTU with Eq 6-38.

$$HTU := \frac{1}{\text{slope}} = 2.31 \,\text{m}$$

Use Eq 6-33 to determine K<sub>1</sub> a from HTU.

$$Q \coloneqq 0.3 \frac{L}{s} \qquad D \coloneqq 0.3m \qquad A \coloneqq \frac{\pi}{4} \cdot D^2 = 0.071 \text{ m}^2$$
$$\begin{bmatrix} K_L \cdot a \end{bmatrix} \coloneqq \frac{Q}{A \cdot HTU} = 1.837 \times 10^{-3} \frac{1}{s}$$

At an air:water ratio of 1000 instead of 100 K<sub>1</sub> a changes from 0.0028 s<sup>-1</sup> to 0.0018 s<sup>-1</sup>.

### b. What is the minimum permissible value for the air:water ratio?

The minimum air:water ratio required for stripping is determined by equation 6-32. For this problem:

$C_0 = 12$	$5 \cdot \frac{\mu g}{L}$ $C_{\text{MBA}} := 25.7 \frac{\mu g}{L}$
$\left[\frac{V}{Q_{min}}\right]$	$:= \frac{C_0 - C_e}{H \cdot C_0} = 44.881$

This calculation assumes that the contaminant's treatment objective is the concentration at a depth of 3.05 m. The 25.7  $\mu$ g/L value falls within the 20 to 40  $\mu$ g/L advisory provided by the USEPA (see p. 2.50).

2. Occasional levels of TCA (1,1,1-trichloroethane) in the source water to the plant in Example 6.2 spike up to 0.5 mg/L. Would the design be able to handle this or, if not, what changes in the design would you propose?

As per p. 2.49, the MCLG for TCA is 200  $\mu g/L.$ 

$$C_{\text{MAV}} = 0.5 \frac{\text{mg}}{\text{L}} = 500 \cdot \frac{\mu \text{g}}{\text{L}} \quad C_{\text{MAV}} = 200 \frac{\mu \text{g}}{\text{L}}$$

From T 6-2, the Henry's Law Constant for TCA (trichloroacetic acid) at 15°C is,

 $H_{TCA} := 0.487$ 

Calculate the minimum air:water ratio using Eq 6.32.

	$\frac{C_0 - C_e}{1.232}$
Q <sub>min</sub>	$H_{\text{TCA}} \cdot C_0 = 1.232$

The tower's air:water ratio is much greater than the minimum air:water ratio; therefore, the design should be able to hand this spike.

### 3. Adapt the GAC adsorption design in Example 6.3 on the basis that it might be possible that this higher TCA levels encountered in Q2 might persist over extended periods.

Strategy: Adapt the solution in in 6-3 for an inlet concentraiton of 500 µg/L.

$$\underbrace{V}_{s} := 1.10 \frac{\text{m}^{3}}{\text{s}} \quad \underbrace{C_{oo}}_{s} := 500 \frac{\mu \text{g}}{\text{L}} \quad \underbrace{C_{oo}}_{s} := 5 \frac{\mu \text{g}}{\text{L}} \quad \left[\frac{\text{V}}{\text{Q}}\right] := 7$$

Assume off-gas temp is 15°C, RH = 100%, relative humidity of adsorber 40%, air temp entering adsorber is 25°C.

Calculate off-gas TCA concentration leaving the air stripper.

$$\left[y_{e}(15)\right] := \frac{C_{0} - C_{e}}{\left[\frac{V}{Q}\right]} = 70.714 \cdot \frac{\mu g}{L}$$

Calculate the TCA gas-phase concentration entering the adsorber (decreased slightly due to heating).

$$\left[y_{e}(25)\right] := \left[y_{e}(15)\right] \cdot \frac{273 + 15}{273 + 25} = 68.341 \cdot \frac{\mu g}{L}$$

Calculate the best possible GAC usage rate, assume no mass transfer resistance. Governing equations:

GAC\_Usage = 
$$\frac{y_e}{q_e \cdot M}$$

Combine Eqs 6-55 and 6-56 to calculate the absorbed phase concentration.

$$q_{e} = \frac{W_{0} \cdot \rho_{l}}{M} \exp \left[\frac{-B}{\alpha^{2}} \cdot \left(R \cdot T \cdot \ln\left(\frac{P_{s}}{P}\right)\right)^{2}\right]$$

Known constants:

$$W_{0} := 0.46 \frac{\text{cm}^{3}}{\text{gm}} \qquad \rho_{1} := 1.33 \frac{\text{gm}}{\text{cm}^{3}} \qquad M := 133.4 \frac{\text{gm}}{\text{mol}} \qquad B := 3.22 \cdot 10^{-5} \frac{\text{cm}^{6}}{\text{cal}^{2}} \qquad R := 0.08205 \frac{\text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}$$

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$$T_{s} = 298K$$
  $P_{s} = 78.8mm_{Hg} = 1.051 \times 10^{4} Pa$ 

Determine P by converting  $y_e$  as follows:

$$P := \left[ y_e(25) \right] \cdot R \cdot T \cdot \frac{1}{M} = 1.269 \text{ Pa} \qquad P = 9.52 \times 10^{-3} \cdot \text{mm}_H\text{g}$$

Now calculate  $\alpha$  using 6-57

 $\eta := 1.4313$  from CRC 85th edition

$$\alpha := \frac{\left(\eta^2 - 1\right) \cdot M}{\left(\eta^2 + 2\right) \cdot \rho_1} = 25.979 \cdot \frac{\mathrm{cm}^3}{\mathrm{mol}}$$

Now calculate q<sub>e</sub>.

$$q_{e} := \frac{W_{0} \cdot \rho_{l}}{M} \exp \left[\frac{-B}{\alpha^{2}} \cdot \left(R \cdot T \cdot \ln\left(\frac{P_{s}}{P}\right)\right)^{2}\right] = 1.178 \times 10^{3} \cdot \frac{\mu \text{mol}}{\text{gm}}$$

Then calculate GAC usage.

GAC\_Usage := 
$$\frac{\left[y_e(25)\right]}{q_e \cdot M} = 4.351 \times 10^{-4} \frac{\text{kg}}{\text{m}^3}$$

Calculate mass of GAC required and the bed life of the GAC adsorber.

EBCT := 2.5s 
$$v_s := 0.5 \frac{m}{s}$$
  $\rho_F := 531 \frac{kg}{m^3}$   
Mass\_GAC := EBCT·V· $\rho_F = 1.46 \times 10^3$  kg

Now determine the bed life:

$$Vol\_Air\_Treated := \frac{Mass\_GAC}{GAC\_Usage} = 3.356 \times 10^{6} \cdot m^{3}$$
$$GAC\_Bed\_Life := \frac{Vol\_Air\_Treated}{V} = 35.316 \cdot day$$

If 500 µg/L TCA levels persist, the mass of GAC required does not change, but bed life falls from 77 days to 35 days.

### 4. What would the effect be on the bubble aeration stripping design in Example 6.4 if the radon levels have to be reduced to 100 pCi?

Retention time in the single tank remains the same, but air flow rate and power requirements will change.

First deterine the air:water ratio needed for stripping (assume a safety factor of 2).

 $\sum_{\mathbf{Q}} = 6000 \frac{\text{pCi}}{\text{L}} \qquad \sum_{\mathbf{Q}} = 100 \frac{\text{pCi}}{\text{L}} \qquad \text{H} = 4.08 \qquad \text{SF} = 2$  $\left[\frac{\text{V}}{\text{Q}}\right] := \frac{\text{C}_0 - \text{C}_e}{\text{H} \cdot \text{C}_e} \cdot \text{SF} = 28.922$ 

The air:water ratio increases from ~10 to ~30.

Now determine the air flow rate.

$$Q := 0.2191 \frac{\text{m}^3}{\text{s}}$$
$$V := \left[\frac{\text{V}}{\text{Q}}\right] \cdot \text{Q} = 6.337 \frac{\text{m}^3}{\text{s}}$$

The increase in air:water ratio causes an increase in air flow rate from 2.191 m<sup>3</sup>/s to 6.34 m<sup>3</sup>/s.

Calculate the power requirements.

First determine the air mass flow rate.

$$\rho_{air} \coloneqq 1.24 \frac{\text{kg}}{\text{m}^3}$$

 $G_{me} := V \cdot \rho_{air} = 7.858 \frac{kg}{s}$ 

Use the inlet air pressure calculated in the example

$$P_{inb} \coloneqq 150290 \frac{N}{m^2}$$

Now find total blower power using Eq 6-49.

$$R_{g} \coloneqq 286.7 \frac{J}{\text{kg} \cdot \text{K}} \qquad T_{air} \coloneqq 293.15 \text{K} \qquad n_{\alpha} \coloneqq 0.238 \qquad \text{Eff}_{b} \coloneqq 0.35 \qquad P_{out} \coloneqq 1 \text{atm}$$

$$P_{blower} \coloneqq \frac{G_{me} \cdot R_{g} \cdot T_{air}}{1000 \frac{W}{\text{kW}} \cdot n_{\alpha} \cdot \text{Eff}_{b}} \cdot \left[ \left( \frac{P_{inb}}{P_{out}} \right)^{n_{\alpha}} - 1 \right] = 779.871 \cdot \text{kW}$$

Blower power increases from 272 kW to 780 kW.

### 5. The surface aeration system in Example 6.6 is considered for doing the same as in Q4, reducing radon from 6000 pCi to 100 pCi. What is the easiest way to redesign the aeration system?

Options:

1. Increase power ... the clearwell is existing and plant flow rate will not change.

2. Divide the existing tank into multiple tanks ... low cost and lower operating costs than just increasing power.

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The clearwell is existing and plant flow rate will not change.

Constants:

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First try increasing the power input per unit volume.

Use the equaitons provided in the example to determine the effluent concentration and by trial and error increase the power requirement until it falls below 100 pCi.

$$\begin{bmatrix} \frac{1}{V} \end{bmatrix} := 196$$
$$\begin{bmatrix} K_{L} \cdot a(O_{2}) \end{bmatrix} := 2.9 \cdot 10^{-5} \left( \begin{bmatrix} \frac{P}{V} \end{bmatrix} \right)^{0.95} \cdot \frac{1}{s} = 4.366 \times 10^{-3} \frac{1}{s}$$

$$\begin{bmatrix} \mathbf{K}_{\mathbf{L}} \cdot \mathbf{a} \end{bmatrix} := \begin{bmatrix} \mathbf{K}_{\mathbf{L}} \cdot \mathbf{a} (\mathbf{O}_{2}) \end{bmatrix} \cdot \left( \frac{\begin{bmatrix} \mathbf{D}_{\mathbf{l}}(\mathrm{radon}) \end{bmatrix}}{\begin{bmatrix} \mathbf{D}_{\mathbf{l}}(\mathbf{O}_{2}) \end{bmatrix}} \right)^{0.6} \cdot \left( 1 + \frac{1}{\mathrm{H} \cdot 40} \right)^{-1} = 3.431 \times 10^{-3} \frac{1}{\mathrm{s}}$$

$$\sum_{\mathbf{k} \in \mathbf{A}} := \frac{C_0}{1 + \left[K_L \cdot a\right] \cdot \frac{V}{Q}} = 99.938 \cdot \frac{pCi}{L}$$

At a power input per unit volume of 196 W/m<sup>3</sup>, the desired reduction in radon can be achieved.

However this system consumes an enormous amount of power, so instead try to divide the tank into sections while leaving the power input unchanged.

$$\left\lfloor \frac{P}{V} \right\rfloor := 35 \qquad \left[ K_{L} \cdot a \right] := 6.7 \cdot 10^{-4} \frac{1}{s} \qquad \tau := 1.5 hr$$

Use the equation provided in the example and by trial and error, determine n, the number of tanks required to **attempt to** achieve the desired reduction in radon.

$$n \coloneqq 10^{6} \qquad \underset{\text{Constant}}{\text{Constant}} \equiv 6000 \frac{\text{pCi}}{\text{L}}$$
$$\underset{\text{Constant}}{\text{Constant}} \equiv \frac{\text{Constant}}{\left[1 + \left(\left[\text{K}_{L} \cdot a\right] \cdot \frac{\tau}{n}\right)\right]^{n}} = 161.019 \cdot \frac{\text{pCi}}{\text{L}}$$

The desired **radon reduction cannot be achieved by using multiple tanks**. Therefore, although undesirable, power input rate will have to be increased.

## 6. The spray aeration system in Example 6.7 is less than 30% effective in removing $H_2S$ . What possibilities would you consider to get the efficiency to about 60%

Options considered:

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1. change the nozzle type to increase the air-to-water surface available for mass transfer

2. increase pump power

The spray aeration system efficiency is governed by,

$$\left[H_2 \cdot S\_Removal\right] = \frac{C_0 - C_e}{C_0}$$

Under the original conditions, the following variables apply.

$$C_{\rm QV} := 1.0 \frac{\rm mg}{\rm L} \qquad \alpha_0 := 0.860 \qquad D_{\rm I} := 1.5 \cdot 10^{-5} \frac{\rm cm^2}{\rm s} \qquad C_{\rm V} := 0.45 \qquad h := 28m \qquad \alpha_{\rm V} := \frac{90}{180} \cdot \pi = 1.571 \qquad d_{\rm p} := 0.1 \rm cm$$

To calculate effluent concentration, first calculate exit velocity and time of contact.

$$v_{d} \coloneqq C_{v} \cdot \sqrt{2 \cdot g \cdot h} = 10.545 \frac{m}{s}$$
$$t \coloneqq \frac{2 \cdot v_{d} \cdot \sin(\alpha)}{g} = 2.151 s$$

Then calculate the overall mass transfer coefficient

$$K_{L} := 2 \cdot \left(\frac{D_{l}}{\pi \cdot t}\right)^{0.5} = 2.98 \times 10^{-3} \cdot \frac{cm}{s}$$
$$a := \frac{6}{d_{p}} = 60 \cdot \frac{1}{cm}$$
$$\left[K_{L} \cdot a\right] := K_{L} \cdot a = 0.179 \cdot \frac{1}{s}$$

Now the effluent liquid-phase concentration of  $\rm H_2S$  can be calculated.

$$C_{S0} := \frac{C_0}{\alpha_0} = 1.163 \cdot \frac{mg}{L}$$
$$C_{Se} := C_{S0} \cdot e^{\left(-\alpha_0 \cdot \left[K_L \cdot a\right] \cdot t\right)} = 0.835 \cdot \frac{mg}{L}$$

 $C_{\text{NMRA}} = \alpha_0 \cdot C_{\text{Se}} = 0.718 \cdot \frac{\text{mg}}{\text{L}}$ 

Finally removal efficiency is calculated.

$$\left[H_2 \cdot S\_Removal\right] := \frac{C_0 - C_e}{C_0} = 0.282$$

To the following variables can be modified:

- 1. velociy coefficient of nozzle (max is 0.95)
- 2.  $\alpha$ , but 90° already provides the maximal contact time, so modification will not improve the result
- 3. h, by replacing the pump with a pump capable of providing a greater level of head
- 4. d<sub>p</sub>, sauter mean diameter of the water drop

It is possible to reach the desired to efficiency by selecting a different nozzle (the pump does not need to be replaced). The efficiency is achieved by selecting a nozzle with the maximum possible velocity coefficient and a SMD of 0.05 cm rather than 0.1 cm (however, I am unsure whether this sort of nozzle is commonly available). The increased resistance that occurs in the nozzle will likely significantly increase power requirements.

 $C_{\text{MM}} = 0.95 \text{ d}_{\text{MM}} = 0.05 \text{ cm}$ 

Using the new values, recalculate efflucent concentration and removal efficiency.

$$C_{\text{vec}} := C_0 \cdot e^{-\left[-\alpha_0 \cdot 2 \cdot \left[\frac{D_1}{\frac{2 \cdot \left(C_v \cdot \sqrt{2 \cdot g \cdot h}\right) \cdot \sin(\alpha)}{g}}\right]^{0.5} \cdot \frac{6}{d_p} \cdot \frac{2 \cdot \left(C_v \cdot \sqrt{2 \cdot g \cdot h}\right) \cdot \sin(\alpha)}{g}\right]}{= 0.383 \cdot \frac{mg}{L}}$$

 $\left[H_2 \cdot S\_Removal\right] := \frac{C_0 - C_e}{C_0} = 0.617$