Lecture 11  Air stripping

Used to remove volatile organic compounds (VOCs), ammonia, H₂S

Basic principle: mass exchange between gas and water phases

Henry's Law: \[ \frac{C_G}{C_W} = H' \]

\( H' \) = dimensionless Henry's Law coeff.
\( C_G \) = conc. in gas (moles/m³)
\( C_W \) = conc. in water (moles/m³)

or: \[ \frac{P}{C_W} = H \]

\( H \) = dimensional Henry's Law coeff. (atm m³/mol)
\( P \) = partial pressure of gas (atm)
\( H' = H/RT \)

\( R \) = gas const = 8.206 × 10⁻⁵ atm m³/(mol °K)
\( T \) = absolute temp. (°K)

Two-film theory: Mass transfer between liquid and gas is limited by diffusion through thin films at water-gas interface

In this example, \[ \frac{C_{sa}}{C_{sw}} = H' < 1 \]
For VOCs, $H' >> 0.01$

Only water-side film controls

![Diagram](image)

Rate of mass transfer $= \frac{dm}{dt} = -D_w A \left[ \frac{C_a/(H'-C_w)}{S_w} \right]$

- $m$ = mass
- $S_w$ = thickness of water-side film
- $D_w$ = molecular diffusion coeff. for water
- $A$ = interface area between air + water

Examples of $H'$

<table>
<thead>
<tr>
<th>Compound</th>
<th>$H'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCE (trichloroethylene)</td>
<td>0.63</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>0.98</td>
</tr>
<tr>
<td>$O_2$</td>
<td>2.6</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.24</td>
</tr>
<tr>
<td>Ammonia gas</td>
<td>0.73</td>
</tr>
</tbody>
</table>

(Note: pH must be raised to convert ionic $NH_4^+$ (ammonium) to gaseous $NH_3$ (ammonia):

$NH_3$ (percent) = $100/\left(1 - 1.75 \times 10^9 [H^+] \right)$)

Note: convert conc in moles/liter to conc in g/liter by multiplying by molecular weight (g/mole)
Vapor pressure defines the "saturation" concentration of a chemical in a gas.

V.P. = partial pressure of a chemical in a gas phase in equilibrium with the pure chemical.

Example: head space in closed bottle of liquid. ICE will be at V.P.

If V.P. > 1.3 x 10^{-3} atm, compound is defined as volatile.

Goal of treatment process design is to maximize

\[
\frac{dm}{dt} = -D_w A \left[ \frac{Ca/H' - C_w}{S_w} \right]
\]

C_w is fixed (influent conc.)

D_w, H' are essentially fixed (could change temp.)

A is increased by splashing water to form smaller droplets

S_w is decreased by increasing turbulence

(Ca/H' - C_w) is increased by decreasing Ca

Accomplished via counter-current air stripping tower - pg 4

Water with compounds to be stripping splashes down through tower film (maximizing A), clean air is drafted upward (minimizing Ca).
Design of an Air-Stripping Tower

- **Contaminated Water Inlet**
- **Air Flow**
- **Water Flow**
- **Air Diffuser**
- **Tower Packing**
- **Gas Monitoring Probe**
- **Exhaust**
- **Water Spray**
- **Treated Water Outlet**
- **Blower**

Mass balance for air stripper:

\[ Q_w, C_{in} \quad \Downarrow \quad Q_a, G_{out} \quad \Downarrow \quad \text{Air} \quad \text{out} \]

\[ Q_w = \text{water flow rate} \quad [L^3/T] \]
\[ Q_a = \text{air flow rate} \quad [L^3/T] \]
\[ C_{in} = \text{influent water conc.} \quad [M/L^3] \]
\[ C_{out} = \text{effluent water conc.} \]
\[ G_{in} = \text{influent air conc \quad [M/L^3]} \]
\[ G_{out} = \text{effluent air conc (set by env'l regulations)} \]
\[ z = \text{height above bottom of air stripper \quad [L]} \]
\[ C(z) = \text{water conc at } z \]
\[ G(z) = \text{air conc at } z \]

Mass balance between 0 and z:

Mass in \quad \quad Mass out

\[ Q_w C(z) + Q_a G_{in} = Q_w C_{out} + Q_a G(z) \quad (1) \]

Assume \( G_{in} = 0 \)

\[ G(z) = \frac{Q_w}{Q_a} (C(z) - C_{out}) \quad (2) \]

For overall air stripper

\[ G_{out} = (Q_w/Q_a) (C_{in} - C_{out}) \quad (3) \]

With equilibrium per Henry's Law

\[ G_{out} = H' C_{in} = \frac{Q_w}{Q_a} (C_{in} - C_{out}) \quad (4) \]

Defines minimum air to water flow rate ratio

\[ \left( \frac{Q_a}{Q_w} \right)_{\text{min}} = \frac{C_{in} - C_{out}}{H' C_{in}} = \frac{1}{H'} \quad (5) \]
Stripping factor, \( S = \frac{Q_a}{Q_w} H' \quad (6) \)

number of minimum air-to-water ratios needed for high efficiency stripping

In ideal case, \( S = 1 \)

Practically, \( S = 2 \) to \( 10 \), \( 3.5 \) is optimal

If \( S < 1 \), air stripper cannot achieve desired removal

Required air stripper height is function of mass transfer kinetics:

Mass balance for differential element of length \( \Delta z \) at height \( z \) inside tower:

\[ Q_c(z+\Delta z) - Q_c(z) = \frac{dm'}{dt} a \Delta V \quad (7) \]

\( \uparrow \)

contaminant mass in

mass in water

inflow

\( \uparrow \)

mass in water outflow

\( \frac{dm'}{dt} = \text{mass flux per unit area across air-water interface} \left[ \frac{M}{L^2 T} \right] \)

\( a = \text{interface area per unit volume of tower} \left[ \frac{L^2}{L^3} \right] \)

\( \Delta V = \text{volume in differential element} \left[ L^3 \right] \)

\( A_T = \text{cross-section area of tower} \left[ L^2 \right] \)

check units:

\[ \frac{L^3}{T} \cdot \frac{M}{L^3} = \frac{L^3}{T} \cdot \frac{M}{L^3} = \frac{M}{L^2 T} \cdot \frac{L^2}{L^3} \cdot L^3 = \frac{M}{T} \checkmark \]
From thin-film theory with water-side control:

$$\frac{dm'}{dt} = -D_W \frac{G(z)/H' - C(z)}{\varepsilon_W}$$ (8)

$$= \frac{D_W}{\varepsilon_W} (C(z) - C_{eq}(z))$$ (9)

$$= K_L (C(z) - C_{eq}(z))$$ (10)

$K_L$ = liquid-phase mass transfer coeff
(piston velocity) = [L/T]

$C_{eq}$ = water conc. in equilibrium
with gas conc. = $G/H'$

Back to mass balance:

$$Q_w C(z + \Delta z) - Q_w C(z) = K_L (C(z) - C_{eq}(z)) \cdot A_t \Delta z$$ (11)

$$\frac{Q_w}{A_t K_L a} \frac{C(z + \Delta z) - C(z)}{\Delta z} = C(z) - C_{eq}(z)$$ (12)

In limit as $\Delta z \to 0$

$$\frac{Q_w}{A_t K_L a} \frac{dC}{dz} = C(z) - C_{eq}(z)$$ (13)

$$\frac{Q_w}{A_t K_L a} \frac{dC}{C(z) - C_{eq}(z)} = dz$$ (14)

$$\frac{Q_w}{A_t K_L a} \int_{C_{in}}^{C(z)} \frac{dC}{C - C_{eq}} = \int_{0}^{L} dz = L \text{ req'd tower height}$$ (15)
To solve, need \( c_{eq} \) as function of \( C \).

From Eq (2):

\[
G(z) = \frac{Q_w}{Q_a} \left( C(z) - C_{out} \right) \quad (2)
\]

\[
c_{eq}(z) = \frac{G(z)}{H'} = \frac{\left( \frac{Q_w}{Q_a} \right) \left( C(z) - C_{out} \right)}{H'} \quad (16)
\]

\[
L = \frac{Q_w}{A_KLa} \int_{C_{out}}^{C_{in}} \frac{dc}{C - \left( \frac{Q_w}{Q_a} \right) \frac{C - C_{out}}{H'}} \quad (17)
\]

\[
L = \frac{Q_w}{A_KLa} \left[ \frac{1}{1 - \left( \frac{Q_w}{Q_a} \right) / H'} \right] \ln \left[ \frac{C_{in} + \left( C_{out} - C_{in} \right) \left( \frac{Q_w}{Q_a} \right) / H'}{C_{out}} \right] \quad (18)
\]

Since \( S = \left( \frac{Q_a}{Q_w} \right) H' = \) stripping factor

\[
L = \frac{Q_w}{A_KLa} \left( \frac{S}{S-1} \right) \ln \left[ \frac{1 + \left( C_{in} / C_{out} \right) (S-1)}{S} \right] \quad (19)
\]
For design, stripper tower is represented as a stack of transfer units:

\[ L = H_{TU} \times NTU \]

\[ H_{TU} = \text{height of transfer unit} = \frac{Q_w}{A_t K_{L\alpha}} \]

Generally \( \frac{Q_w}{A_t} \leq 20 \ \text{gpm} \ \text{ft}^{-2} = 0.014 \ \text{m} \ \text{s}^{-1} \)

Manufacturer can supply \( K_{L\alpha} \) values vs. temperature and flow rate (but best to test in pilot studies before final design) \( K_{L\alpha} = 0.01 \) to \( 0.05 \) sec\(^{-1}\) for VVCS

Use \( \frac{Q_w}{A_t} = 20 \ \text{gpm} \ \text{ft}^{-2} \) \( \rightarrow \) known \( Q_w \) to find \( A_t \)

Use \( K_{L\alpha} \) data, \( Q_w/A_t \) to find \( HTU \)

\[ NTU = \text{number of transfer units} \]

\[ = \frac{S}{S-1} \ln \left[ \frac{C_{in}}{C_{out}} \left( \frac{S-1}{S} \right) + \frac{1}{S} \right] \]

Design graph (pg. 10) gives fraction removed \( \left( \frac{C_{in} - C_{out}}{C_{in}} \right) \) vs. \( S \) and \( NTU \)

Note marginal decrease in \( NTU \) for \( S > 3 \)
Figure by MIT OCW.

Full design procedure is given by:


MWH, 2005 gives same procedure

Design procedure considers pressure drop for air flow through tower, a cost factor in that blower adds to power consumption.

Kuo, 1999 (handout) gives simplified procedure:

Get $H'$ for contaminant of concern

Select $S$ between 2 and 10 - $S = 3.5$ is good estimate

Compute $\frac{Q_a}{Q_w} = \frac{S}{H'}$

From known $Q_w$, find $A$ such that $\frac{Q_w}{A} \leq 20$ gpm = $0.014 \ m^2/s$

Determine desired treated water conc., $C_{out}$

From known $C_{in}$, desired $C_{out}$ and estimated $S$, compute

$$NTU = \left( \frac{S}{S-1} \right) \ln \left[ \frac{C_{in}}{C_{out}} (\frac{S-1}{S}) + \frac{1}{S} \right]$$

From manufacturer data for $K_{va}$, compute

$$HTU = \frac{Q_w}{A K_{va}}$$

Compute tower height $L = NTU \cdot HTU$