
You may have noted that vapor-liquid equilibrium (VLE) data for distillation is always at a given pressure (and no specified temperature), whereas data for absorption/stripping, for example Henry’s law \( y_A = m x_A \), are at a given pressure and temperature.

To understand this consider a column with given pressure and assume we know the liquid stage composition of A \( x_A \) (or vapor stage composition \( y_A \)). In a distillation column (separating A and B) the stage temperature is then given, but not in a absorber/stripper (transferring A between inerts B and C). Explain why using Gibbs’ phase rule.

Comment: The important implication of this is the following:

1. In distillation we have a "boiling mixture" on all stages. If you in a distillation column decrease the temperature of the feed (so maybe it is subcooled), then this will lead to some condensation of vapor at the feed stage (which you would have to compensate for by increasing the boilup) but the temperature change inside the column will be very small.

2. In absorption/stripping we do NOT have a "boiling mixture". If you in an absorption column decrease the temperature of the liquid feed (in the top), then this will lead to a decrease in temperature in the entire column (the vapor will also be cooled but it does not condense because it is "inert", for example, air will not condense).

Thus, one can independently control temperature and composition in absorption but not not in distillation.

Problem 2. Absorption of CO2 in water-amine solution

This exercise will give you some understanding of the problems with the "moon landing" project on Mongstad (which is even more difficult because the gas from a natural gas power plant contains less than 5% CO2).

A combustion gas (22 kmol/s) from a large coal-fired power plants contains 11.76% CO2 (mole-%); the rest is air with a bit low O2-contents. We want to remove about 90% of the CO2 so that the cleaned gas contains 1.16% CO2. This is done by contacting the combustion gas with a water-amine solution in a packed absorption column at about 60°C and 1.2 bar. The water-amine feed solution contains 2.19% CO2 (it comes from a stripping column used for regeneration) and the enriched solution leaving the bottom contains 5.32% CO2.

\(^1\)The water-amine liquid solution contains about to 11% MEAmine, but this is not important because you shall treat the water-amine solution as a combined inert.
(a) Assume constant inert flows for air (\(V'\)) and water-amine (\(L'\)) through the column. Find \(L'\) and \(V'\), the total feed of amine solution (\(L_0\)) and the product rates (\(L_N\) and \(V_0\)).

(b) What is the diameter of the column given that the superficial gas velocity (neglecting the area taken by the packings and liquid) is 2 m/s.

(c) Equilibrium data is given in the table below. Is it reasonable to use Henry’s law in this case?

(d) Determine the number of stages required (using a graphical solution).

\[y_{n+1} = \frac{L_0}{V_{n+1}} x_n + \frac{y_1 V_1 - x_0 L_0}{V_{n+1}}\]

It is not quite linear but it goes through the points \((x_0, y_1)\) and \((x_N, y_{N+1})\) (explain why!). To simplify you may assume that the operating line is a straight line between these two points (which corresponds to using a constant \(\frac{y_{N+1} - y_1}{x_N - x_0}\)).

Table: Equilibrium data for CO2 and water-MEAmine at 1.2 bar and about 60°C (inert air present).

<table>
<thead>
<tr>
<th>(x_{CO2} (%))</th>
<th>(y_{CO2} (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.227</td>
<td>1.162</td>
</tr>
<tr>
<td>3.001</td>
<td>2.917</td>
</tr>
<tr>
<td>3.339</td>
<td>3.783</td>
</tr>
<tr>
<td>4.101</td>
<td>6.057</td>
</tr>
<tr>
<td>4.700</td>
<td>8.448</td>
</tr>
<tr>
<td>5.324</td>
<td>11.60</td>
</tr>
</tbody>
</table>
Problem 3. Stripping tower with direct steam injection (Problem 11.4-9)

In addition: (c) Use the Kremser formula to check the result from (b) (where you should determine the number of stages graphically).

Note: This column is a “cross” between a distillation column and a stripper. It separates a binary mixture of ethanol-water so from this point of view it is similar to distillation, but without a top section and with direct steam injection instead of a reboiler.
TKP 4105. Solution for exercise stripping/absorption

Problem 1

For a case without reaction, the number of degrees of freedom according to the Gibbs phase rule is

\[ F = C - P + 2 \]

Thus, with two phases \((P=2)\), the number of degrees of freedom (variables that can be specified among the variables \(T\), \(P\) and composition) is equal to the number of components:

\[ F = C \]

For distillation we have \(C = 2\) and specifying \(x_A\) (composition) and \(p\) uniquely determines the system.

For absorption/stripping we have \(C = 3\). We specify \(x_A\) which gives one piece of information (we do not specify the small amount of "inert" gas \(B\) in the liquid). Thus, we have two degrees of freedom left and can specify both \(T\) and \(p\).

Problem 2. Absorption of CO2 in water-amine solution

Based on the given data we have

\[ V_{N+1} = 22 \text{ kmol/s} \]
\[ y_{N+1} = 0.1176 \text{ (CO2 mole fraction)} \]
\[ y_1 = 0.0116 \]
\[ x_0 = 0.0219 \]
\[ x_N = 0.0532 \]

(a) Flow of inert air: \(V' = V_{N+1}(1 - y_{N+1}) = 19.41 \text{ kmol/s.}\)

Overall material balance for CO2 (in=out):

\[ y_{N+1}V_{N+1} + x_0L_0 = x_NL_N + y_1V_1 \]

Assuming the inert flows \(L'\) and \(V'\) are constant through the column gives:

\[ y_{N+1}V' + x_0L' = x_NL' + y_1V' \]

Here we know all the variables except \(L'\). Get:

\[ L'/V' = 3.596 \Rightarrow L' = 69.80 \text{ kmol/s} \]

Then

\[ L_0 = L'/(1-x_0) = 71.36 \text{ kmol/s} \]
\[ L_N = L'/(1-x_N) = 73.72 \text{ kmol/s} \]
\[ V_1 = V'/(1 - y_1) = 19.64 \text{ kmol/s} \]

(b) The superficial gas velocity is \( v[m/s] = V[m^3/s]/A[m^2] \) where \( A \) is the tower cross-sectional area. The molar volume can be found from the ideal gas law and we have \( V_m = RT/p = 8.31 \cdot (273 + 60)/1.2\cdot5 = 0.023 \text{ m}^3/\text{mol} \), and we find that the volumetric flowrate at the bottom (where it is at its maximum) is \( V = 22\cdot3[m^3/s] \cdot 0.023 \text{ m}^3/\text{mol} = 507 \text{ m}^3/s \). To get a gas velocity of \( v = 2 \text{ m/s} \) we then have \( S = \frac{507}{2} = 253.5 \text{ m}^2 \) (tower cross-sectional area) and the tower diameter is \( D = \sqrt{S \cdot 4/\pi} = 18.0 \text{ m} \) (this is REALLY big).

(c) Is it reasonable to use Henry’s law in this case? No, the ratio \( y/x \) varies from 0.52 to 2.18 in the concentration range of interest.

![Figure 1: Determining the number of stages for CO2 absorption](image)

(d) From the diagram we find that about 13 theoretical stages are required. Note that diagram was drawn on a computer which allowed for for non-straight operating line, so with a straight operating line you should get a slightly larger number.
Problem 3. Stripping tower with direct steam injection (Problem 11.4-9)

Figure 2: The column is a cross between a distillation column and a stripper. To show better the "cross", the figure gives notation both for a stripper and distillation column.

Using the distillation notation we have given the following:

\[ x_F = 0.033, \quad x_s = 0, \quad y_D D = 0.99x_F F \]

Also, assuming constant molar flows we have

\[ W = F, \quad D = S \]

We then have from a material balance

\[ x_W W = 0.01x_F F \Rightarrow x_W = 0.01x_F = 0.0033 \]

The equilibrium data are given so we can draw the equilibrium line. A material balance over the bottom gives (since \( y_s = 0 \)) the following operating line:

\[ y_{n+1} = \frac{L}{V} x_n + \frac{x_W W}{V} = \frac{F}{S} (x_n - x_w) \]

The operating line starts in the point \((x_w, 0)\) and ends at the feed line \((q\text{-line})\). Since the feed is liquid the \(q\)-line is vertical.

(a) As we decrease the steam \(S\) the slope of the operating line gets steeper and eventually we get a pinch corresponding to an infinite number of stages.
Normally, the pinch occurs at the feed (where the q-line crosses the equilibrium line), but in some cases the curvature of the equilibrium line (caused by non-ideality) makes the pinch occur somewhere in the middle of the column (see Figure 11.4-12). In our case, it is a bit difficult to tell, but it seems that we have the "normal" case where the pinch occurs at the feed, that is, at the point \((x', y') = (0.033, 0.270)\). The limiting slope of the operating line is then:

\[
\frac{L}{V_{min}} = \frac{F}{S_{min}} = \frac{y' - 0}{x' - x_w} = \frac{0.270}{0.033 - 0.00033} = 8.26
\]

\[
\Rightarrow S_{\min} = \frac{1}{8.26} \frac{0.121 \text{ mol steam}}{\text{mol feed}}
\]

(which agrees with the value in the book).

(b) We use \(S/F = 2 \cdot 0.121 = 0.242\). From the material balance we then get

\[
y_D = 0.99x_F \frac{F}{D} = \frac{0.99 \cdot 0.033}{0.242} = 0.135
\]

From the McCabe-Thiele diagram (starting from the top, but you could start from the bottom) we then get \(N = 5.33\) theoretical stages (maybe this is a bit inaccurate because the book says 5.0).

(c) **Check with Kremser formula.** First we need to find the constant \(m\) in Henry’s law, \(y = mx\). From the equilibrium data we get \(\frac{y}{x}\) equal to

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**Figure 3:** Blue line: Equilibrium line, Black line: operating line

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7
(9.375, 8.75, 8.44, 8.18) for the four nonzero compositions (0.008, 0.02, 0.0296, 0.033). Since the number of stages is most sensitive to the value at small values of \( x \) (see the McCabe-Thiele diagram) we choose to use \( m = 9.375 \). With \( x_0 = 0.033, x_N = 0.00033, y_{N+1} = 0 \) and \( A = \frac{L/V}{m} = 4.13/9.375 = 0.441 \) we then get from Eq.(10.3-22) (since \( y_{N+1} = 0 \)):

\[
N = \frac{\ln\left[ \frac{x_0}{x_N} (1 - A) + A \right]}{\ln(1/A)} = \frac{\ln(55.9 + 0.441)}{\ln(1/0.441)} = 4.92
\]

which is close to the value 5.0 given in the book.