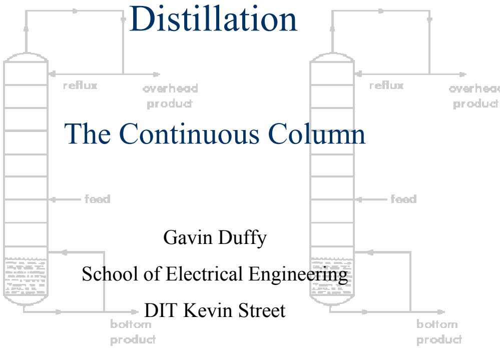
Distillation

The Continuous Column



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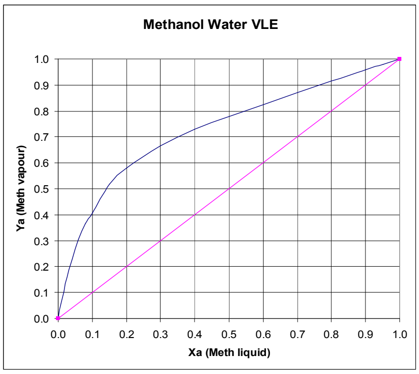
Learning Outcomes

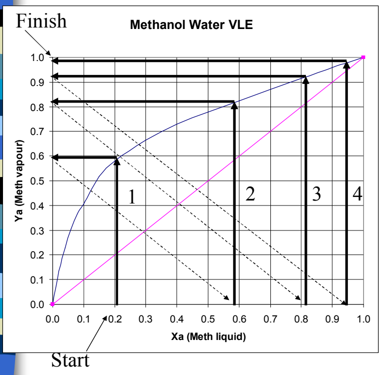
After this lecture you should be able to…..

- Describe how continuous distillation works
- List the major components of a distillation column
- Develop a mathematical model for a continuous column

Recap - VLE for Meth H_2O



Boil and Cool 4 times



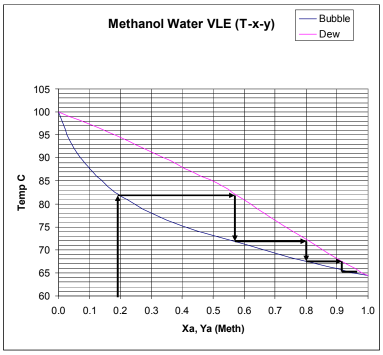
Boiling a liquid with Xa of 0.2 produces a vapour with Ya of 0.57

Boiling a liquid with Xa of 0.57 produces a vapour with Ya of 0.82

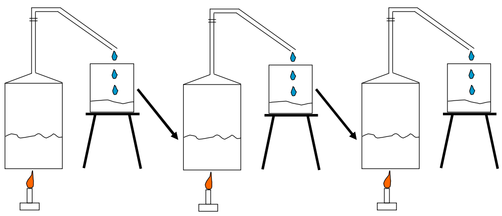
Boiling a liquid with Xa of 0.81 produces a vapour with Ya of 0.93

Boiling a liquid with Xa of 0.93 produces a vapour with Ya of 0.98

Alternatively use T-x-y Diagram

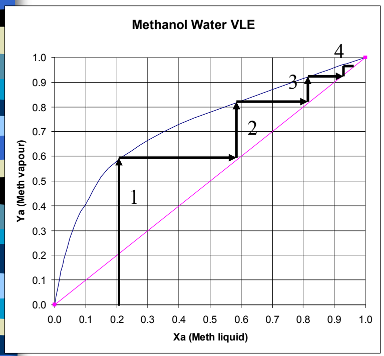


How to separate a binary mixture – Pot still



Boil the mixture, condense the vapour and collect the distillate. Repeat the procedure until the desired purity is obtained.

Each still is a step on the x-y curve

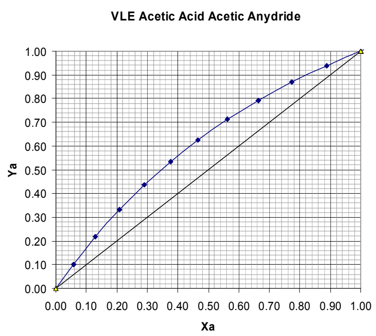


Step off each stage using the x=y line gives the same result

Each step is an ideal stage in distillation

4 ideal stages to go from 20% Meth to 95% Meth

Activity – Count Stages



How many ideal stages are needed to take this system from a feed composition of 0.2 to a distillate composition of 0.95?

Pros and Cons of the pot still?

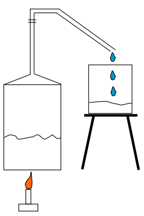
Cannot vaporise all of the mixture

Small amount High purity

Large amount Low purity

Large amounts of energy required

Very slow



Very simple to make

Cheap – minimum components

Flexible – can collect over time before using

How can this be improved?

How to improve the pot still?

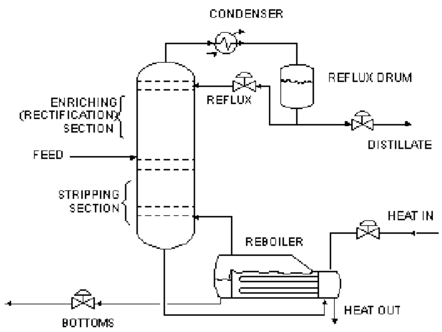
Remember that boiling results in a change of composition, and condensing also results in a change of composition

Therefore, combine the two processes inside the column to improve the distillation process

A distillation column is designed to encourage vapour liquid contact

Falling liquid meets rising vapour. Boiling and condensing do not just occur in the reboiler and the condenser. They happen inside the column also

The Distillation Column



Distillation Column Components

Reboiler – this heats the liquid

Stripping Section – MVC is vapourised

Rectifying Section – LVC is condensed

Trays/Plates – encourage vapour liquid contact

Packing – alternative to trays

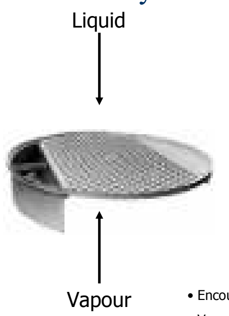
Condenser – Vapour from column is cooled to liquid

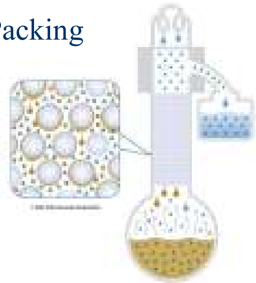
Reflux – condensed vapour can be returned to column

Top product – from condenser

Bottom product – from reboiler

Trays and Packing





- Encourage vapour liquid contact
- Vapour condenses to release LVC
- Liquid uses this energy to boil and release MVC

Column Mass Balance

F, B, D, etc are flow rates in mol/s

X_f etc are mol fractions

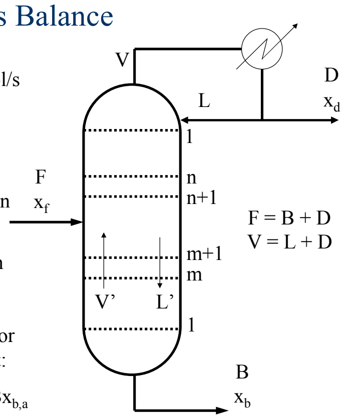
n trays in the rectifying section

m trays in the stripping section

V, L different

Can also write for each component:

$Fx_{f,a} = Dx_{d,a} + Bx_{b,a}$

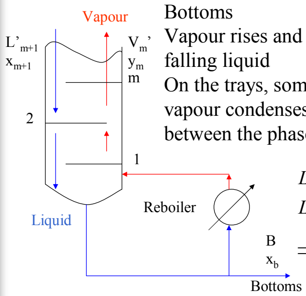


$F = B + D$
$V = L + D$

Activity – Mass balance on Acetic Acid/Acetic Anhydride problem

- A mixture of Acetic Acid and Acetic Anydride containing 40 mol % Acetic Acid is to be separated by distillation. The top product is to be 90 mol % Acetic Acid and the bottom product 10 mol % Acetic Acid.
- The feed is heated to its boiling point. The vapour is condensed but not cooled and some is returned at a reflux ratio of 3 kmol/kmol product.
- Carry out a mass balance on this column

The Stripping Section



Feed flows down column to reboiler
Reboiler heats liquid to BP and vapour rises
Liquid that does not vaporise is removed as Bottoms
Vapour rises and is forced into contact with falling liquid
On the trays, some liquid reboils and some vapour condenses due to heat transfer between the phases - more stages are created

$$L'_{m+1} = V'_m + B$$

$$L'_{m+1} x_{m+1} = V'_m y_m + B x_b$$

$$\Rightarrow y_m = \frac{L'_{m+1}}{V'_m} x_{m+1} - \frac{B}{V'_m} x_b$$

Constant Molal Overflow

The assumption of constant molal overflow is used to simplify the above equations.
It means that for every mole of vapour condensed, 1 mole of liquid is vaporised.
This does not happen in reality but it is an acceptable approximation.
It is based on negligible heat of mixing and heat loss and on constant molar enthalpies
It means that while the liquid and vapour compositions may change the overall flowrate of each is constant through the column, i.e.

$$L_n = L_{n+1} \text{ and } V_n = V_{n+1}$$

Applying constant molal overflow

Stripping Section

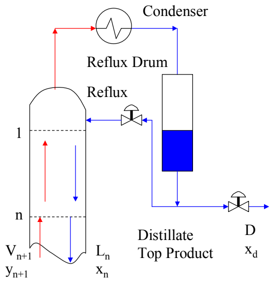
$$y_m = \frac{L'_{m+1}}{V'_m} x_{m+1} - \frac{B}{V'_m} x_b$$

Applying constant molal overflow gives

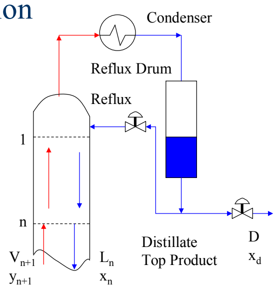
$$y = \frac{L'}{V'} x - \frac{B}{V'} x_B$$

Activity - Rectifying Section

Develop the operating line for the rectifying section



The Rectifying Section



Condenser at the top of the column cools the vapour, collected in the reflux drum

A portion is returned to the column as reflux

Remainder is removed as Distillate or Top Product

Reflux Ratio = Reflux/Distillate

Mass balance on flowrates gives

Vapour = Liquid + Distillate

$$V_{n+1} = L_n + D$$

$$V_{n+1} y_{n+1} = L_n x_n + D x_d$$

$$\Rightarrow y_{n+1} = \frac{L_n}{V_{n+1}} x_n + \frac{D}{V_{n+1}} x_d$$

Applying constant molal overflow

Rectifying Section

$$y_{n+1} = \frac{L_n}{V_{n+1}} x_n + \frac{D}{V_{n+1}} x_d$$

Stripping Section

$$y_m = \frac{L'_{m+1}}{V'_m} x_{m+1} - \frac{B}{V'_m} x_b$$

Applying constant molal overflow gives

$$y = \frac{L}{V} x + \frac{D}{V} x_d$$

$$y = \frac{L'}{V'} x - \frac{B}{V'} x_B$$

Activity – Label this distillation column!

Reflux

Some condensed liquid is removed from the column as distillate. Some is returned. The reflux ratio is the ratio of liquid returned to the column over the amount removed

R = L/D or L = DR

Activity – rewrite the operating line for the rectification section using the reflux ratio.

Rectifying Operating Line

The rectifying operating line is:

$$y = \frac{L}{V}x + \frac{D}{V}x_d$$

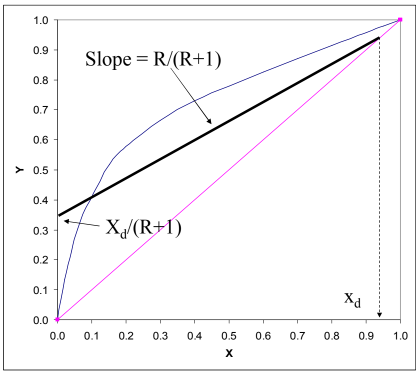
Since L = RD and V = RD+D, we get:

$$y = \frac{RD}{RD+D}x + \frac{D}{RD+D}x_d$$

$$y = \frac{R}{R+1}x + \frac{1}{R+1}x_d$$

Compare this to y = mx + c – it is a straight line

Rectifying line on X-Y Diagram



Stripping Operating Line

The boilup ratio is defined as the ratio of vapour returning to the column to the bottoms product flow:

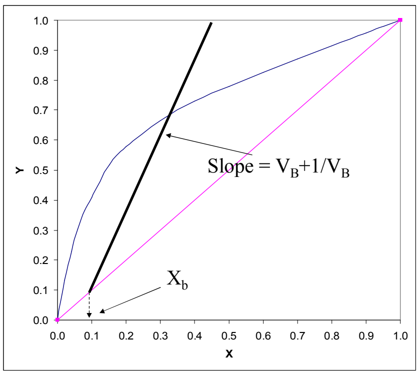
$$V_B = V'/B$$

Therefore, the stripping operating line can be written as

$$y = \frac{V_B + 1}{V_B} x - \frac{1}{V_B} x_B$$

Again of the form y = mx + c, another straight line

Stripping line on X-Y Diagram



Summary – Operating lines

- The rectifying section (upper column)

$$y = \frac{R}{R+1}x + \frac{1}{R+1}x_d$$

- The stripping section (lower column)

$$y = \frac{V_B + 1}{V_B}x - \frac{1}{V_B}x_B$$

- Or

$$y = \frac{L_m}{V_m}x - \frac{B}{V_m}x_b$$

- Note minus sign in stripping line

Activity – Operating lines

A mixture of Acetic Acid and Acetic Anydride containing 40 mol % Acetic Acid is to be separated by distillation. The top product is to be 90 mol % Acetic Acid and the bottom product 10 mol % Acetic Acid.

The feed is heated to its boiling point. The vapour is condensed but not cooled and some is returned at a reflux ratio of 3 kmol/kmol product.

Determine the operating lines for the rectifying and stripping sections and draw them on an equilibrium curve.

To help you:
- Start with the rectifying line – it is easy – just use the reflux ratio.
- Stipping line is harder – we don't know the boilup rate needed. So…
- Determine B and D from an overall mass balance
- Use D and R to give L for rectifying section (L_n)
- Use L and D to give V for rectifying section
- L for stripping section (L_m) comes from F and L_n
- V is the same for both sections as feed enters as liquid
- Use L_m and B and V to give stripping operating line

The intersection of the operating lines

If the feed enters the column as a liquid at its boiling point then the operating lines intersect at x_f. In this case:

$$L_m = L_n + F$$

i.e. the liquid flow in the stripping section is the sum of all of the feed and the liquid flow from the top of the column. All of this liquid will be at the bubble point.

The feed may not be liquid at its boiling point. It might be at a lower temperature or at a higher temperature. There are five possible feed conditions.
What happens to the operating lines if the feed is colder, i.e less than the boiling point?

Activity – Feed Condition

The feed to the column can vary in form. It can be:

- Subcooled liquid
- Bubble point liquid
- Partially vaporised feed
- Dew point vapour
- Superheated vapour

Think, Pair, Share briefly (5 min) what this means for the liquid and vapour flowrates in the stripping and rectifying sections of the column.

The q line

This is used to show the feed condition on the x-y diagram.
It is obtained by writing the two operating lines at their intersection, i.e. at plate n and plate m – the feed plate
An enthalpy balance on the feed plate is then carried out to give the following equation (see C&R Vol 2, 4th Ed. p449):

$$L_m = L_n + qF$$

$$q = \frac{C_p(T_o - T) + \lambda}{\lambda}$$

Where C_p = specific heat capacity
T_o = boiling point of feed
T = temperature of feed
λ = latent heat of vaporisation

What is q?

- q = the enthalpy change needed to bring the feed to a dew point vapour divided by the enthalpy of vaporisation of the feed
- Defined as:

$$q = \frac{\text{Heat to vaporise 1 mol of Feed}}{\text{Molar latent heat of vaporisation of the Feed}}$$

- If the feed is a mixture of liquid and vapour then q is the fraction that is liquid
- For cold feed

$$q = 1 + \frac{c_{pL}(T_b - T_F)}{\lambda}$$

C_{pL} heat capacity of liquid
T_b bubble point
T_F Feed temp
λ Latent heat of vapor'n

- For superheated vapour

$$q = -\frac{c_{pV}(T_F - T_d)}{\lambda}$$

C_{pV} heat capacity of vapour
T_d dew point
T_F Feed temp

The q line equation

Using the above definition of q and a material balance over the whole column we get the q line:

$$y_q = \frac{q}{q-1} x_q - \frac{x_f}{q-1}$$

The two points used to draw the q line are:

1. $y_f = x_f$
2. The intersection point of the other two operating lines

The q line and feed condition

The feed condition can now be described by the q line:

•Subcooled liquid	$q > 1$	q line /
•Bubble point liquid	$q = 1$	q line |
•Partially vaporised feed	$0 < q < 1$	q line \
•Dew point vapour	$q = 0$	q line ---
•Superheated vapour	$q < 0$	q line /

The q line and feed condition

The slope of the q line depends on the feed condition