CHE 306
Stagewise Operations
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Batch Distillation

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Batch Distillation

Continuous distillation produces large amounts of material of constant composition.

If small amounts of material or varying product composition are needed, one has to use batch distillation.
Simple Batch Distillation

still pot

$W, x_W$

$Q_R$

$D, x_D$
Multistage Batch Distillation

\[ D, x_D \]

\[ V_{j+1}, x_{j+1} \]

\[ L_j, x_j \]

\[ W, x_W \]

\[ Q_R \]
Rayleigh Equation

\[ \ln \left( \frac{W_{\text{final}}}{F} \right) = - \int_{x_{W,\text{final}}}^{x_F} \frac{dx_W}{x_D - x_W} \]
1/ plot or fit $y(x)$ equilibrium curve

2/ at a series of $x$ values, find $y-x$

3/ plot $1/(y-x)$ vs. $x$ or fit it to an equation

4/ graphically or numerically integrate from $x_F$ to $x_{W,\text{final}}$ ⇒ area

5/ find the final charge in the still

$$W_{\text{final}} = F e^{-\text{Area}}$$

6/ compute average distillate composition

$$x_{D,\text{avg}} = \frac{Fx_F - W_{\text{final}}x_{W,\text{final}}}{F - W_{\text{final}}} \quad D_{\text{total}} = F - W_{\text{final}}$$
Simpson’s rule:

\[
\text{area} = \frac{x_F - x_{W_{final}}}{6} \left[ f(x_{W_{final}}) + 4f\left(\frac{x_F + x_{W_{final}}}{2}\right) + f(x_F) \right]
\]
Consider a mixture with a constant relative volatility $\alpha$

$$y = \frac{\alpha x}{1 + (\alpha - 1)x}$$

Final charge is given by:

$$\ln\left(\frac{W_{\text{final}}}{F}\right) = \frac{1}{\alpha - 1} \ln\left(\frac{x_{W,\text{final}} (1 - x_F)}{x_F (1 - x_{W,\text{final}})}\right) + \ln\left(\frac{1 - x_F}{1 - x_{W,\text{final}}(1)}\right)$$
Constant-level batch distillation

Solvent switching

Boil off most of the original solvent and add a new solvent continuously so that the second batch distillation is such the amount of the second solvent in the still pot is kept constant.
Consider a mixture with a constant relative volatility $\alpha$

$$\frac{S}{W} = \frac{1}{\alpha} \ln \left( \frac{x_{W,\text{initial}}}{x_{W,\text{final}}} \right) + \frac{\alpha - 1}{\alpha} (x_{W,\text{initial}} - x_{W,\text{final}})$$
Batch Steam Distillation

\[ W, x_w \text{ (water free)} \]

\[ \text{steam} \]

volatile organics

\[ x_D \]

water to waste
steam is sparged directly into the still pot

1/ no need to heat above 100 degrees Celsius
2/ no need for heat transfer equipment
3/ steam results in good mixing of the material in the pot

This technique is used for systems that are immiscible with water
Treat wastes that contain valuable VOCs (glycerine, lube oils, fatty acids, halogenated hydrocarbons)

Only one stage is needed

Mass balance on a water free basis

\[ W_{f\text{inal}} = F \left( \frac{x_D - x_F}{x_D - x_{W_f\text{inal}}} \right) \]

\[ x_D = 1 \text{ if a single VOC} \]
Total moles of water required

\[ n_W = \int_0^{n_{\text{org,total}}} \frac{P_{\text{tot}} - P_{\text{org}}}{P_{\text{org}}} \, dn_{\text{org}} \]

where

\[ P_{\text{org}} = P_{\text{org}}^{\text{sat}} x_{\text{org,water free basis}} \]

Must add condensed water needed to heat the feed and vaporize the VOCs
Multistage Batch Distillation

With a single stage one often cannot get the desired distillate and residue compositions

Place a distillation column above the still

The Rayleigh equation is valid but one has to find a relationship between \( x_D \) and \( x_W \), which is obtained from stage-by-stage calculation.
Neglect accumulation everywhere except the still pot

\[ V_{j+1} = L_j + D \]

\[ V_{j+1}y_{j+1} = L_jx_j + Dx_D \]

\[ Q_c + V_{j+1}H_{j+1} = L_jh_j + Dh_D \]
CMO (Constant Molal Overflow)

\[
y_{j+1} = \frac{L}{V} x_j + \left(1 - \frac{L}{V}\right) x_D
\]

No need for energy balance & L and V will be constant
Constant Reflux Ratio Operation

Use constant reflux ratio and allow $x_D$ to vary

Use McCabe & Thiele diagram for a series of $x_D$ values to find their corresponding $x_W$ values.

\[
\ln \left( \frac{W_{\text{final}}}{F} \right) = - \int_{x_{W,\text{final}}}^{x_F} \frac{dx_W}{x_D - x_W} \quad \Rightarrow \quad W_{\text{final}}
\]
McCabe & Thiele diagram for multistage batch distillation with constant reflux ratio
Variable Reflux Ratio Operation

Vary the reflux ratio and keep $x_D$ constant.

The slope of the operating line will now vary.

Use McCabe & Thiele diagram to find $x_W$ values.
McCabe & Thiele diagram for multistage batch distillation with variable reflux ratio

0 \quad x_{W,2} \quad x_{W,1} \quad 1.0

1.0

x_D

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Need to find the initial slope of the operating line so that $x_W = x_F$.

Need to increase the operating line slope until $x_W = x_{W,\text{final}}$.

Use mass balance around the entire system for the entire operation time to get $W_{\text{final}}$.

\[ F = W_{\text{final}} + D_{\text{total}} \]

\[ Fx_F = W_{\text{final}}x_{W,\text{final}} + D_{\text{total}}x_D \]
Operating time

Usual batch duration including startup and shutdown is around eight-hour shift

\[ t_{batch} = t_{op} + t_{down} \]

Dumping the bottoms, cleanup, loading next batch and heating until reflux starts to appear
From Rayleigh equation

Total distillate amount in kmoles

\[ t_{op} = \frac{D_{total}}{D} \]

Distillate flow rate in kmoles/hr

\[ D_{max} = \frac{V_{max}}{1 + \frac{L}{D}} \]

\[ D = 0.75 \ D_{max} \]

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Energy requirement for the total condenser

\[ Q_c = -V_1 \lambda_{avg} \]

Energy balance around the entire system

\[ Q_R = -Q_c + Dh_D \]