1 Flash Distillation

$y_i = K_i x_i$
$x_i = \frac{z_i}{1+(K_i-1)\frac{V}{F}}$
Rachford-Rice: $f\left(\frac{V}{F}\right) = \sum_{i=1}^{N} \frac{(K_i-1)z_i}{1+(K_i-1)\frac{V}{F}} = 0$

2 Column Distillation

$F = B + D$
$Fz = Dx_D + Bx_B$
$F\hat{h}_F + \dot{Q}_{\text{cnd}} + \dot{Q}_{\text{rb}} = D\hat{h}_D + B\hat{h}_B \qquad \dot{Q}_{\text{cnd}} < 0 \qquad \dot{Q}_{\text{rb}} > 0$
$V = L + D$
$Fx_F = Vy_V + Lx_L$
$q \equiv L/F$
$f \equiv V/F$
$R \equiv L_0/D$

2.1 Condenser

$y_1 = x_D = x_0$
$V_1 = L_0 + D \Rightarrow V_1 = D(1 + \frac{L_0}{D})$
$V_1\hat{H}_1 + Q_{\text{cnd}} = L_0\hat{h}_0 + D\hat{h}_D \qquad \hat{h}_D = \hat{h}_0$
$\dot{Q}_{\text{cnd}} = V_1(\hat{h}_0 - \hat{H}_1) = V_1\Delta_{\text{vap}}\hat{H}$

2.2 Condenser and Stage 1

$V_2 = L_1 + D$
$V_2y_2 = L_1x_1 + Dx_D$
$\dot{Q}_{\text{cnd}} + V_2\hat{H}_2 = L_1\hat{h}_1 + D\hat{h}_D$
$\hat{h}_1 = \hat{h}_1(x_1) \quad \hat{H}_2 = \hat{H}_2(y_2) \quad x_1 = x_1(y_1)$

2.3 Reboiler

$\bar{V}_n = \bar{L}_{n-1} - B$
$\bar{V}_n y_n = \bar{L}_{n-1}x_{n-1} - Bx_B$
$\bar{V}_n\hat{H}_n = \bar{L}_{n-1}\hat{h}_{n-1} - B\hat{h}_B + \dot{Q}_{\text{rb}}$

2.4 Lewis Method

$L/V = \frac{R}{R+1} \qquad D/V = \frac{1}{R+1}$
$y_{n+1} = \frac{L}{V}x_n + (1 - \frac{L}{V})x_D \Rightarrow y = \frac{R}{R+1}x + \frac{1}{R+1}x_D$
$r_{\text{b}} \equiv B/\bar{V}$
$\bar{L}/\bar{V} = \frac{r_{\text{b}}+1}{r_{\text{b}}}$
$y_n = \frac{\bar{L}}{\bar{V}}x_{n-1} - (\frac{\bar{L}}{\bar{V}} - 1)x_B \Rightarrow y = \frac{r_{\text{b}}+1}{r_{\text{b}}}x_{n-1} - \frac{1}{r_{\text{b}}}x_B$
$q = \frac{\bar{L} - L}{F} \approx \frac{\hat{H}_V - \hat{h}_F}{\hat{H}_V - \hat{h}_L}$
$\bar{L} = L + qF$
$\bar{L} = \bar{V} + B$
$L = \left(\frac{L}{D}\right)D$

2.5 Murphree Efficiency

$\eta_{\text{MV}} = \frac{y_n - y_{n+1}}{y_n^* - y_{n+1}} \qquad \eta_{\text{ML}} = \frac{x_n - x_{n-1}}{x_n^* - x_{n-1}}$
$y_n^* \equiv$ fraction that would be in equilibrium with x_N
$x_n^* \equiv$ fraction in equilibrium with y_N

2.6 McCabe-Thiele Method

$(L/V)_{\min} = \frac{y_{\text{ref}}(x_D) - y_{\text{VLE}}(x_F)}{x_D - x_F} \qquad (L/D)_{\min} = \frac{(L/V)_{\min}}{1-(L/V)_{\min}}$
Feed Line: $y = \frac{q}{q-1}x - \frac{1}{q-1}z$
Rect. Line: $y_{\text{rect}}(x) = \frac{R}{R+1}x + \frac{1}{R+1}x_D$
$y_{\text{rect},n+1}(x) = \frac{L}{V}x_n + \left(1 - \frac{L}{V}\right)x_D \qquad \frac{L}{V} = \frac{L/D}{L/D+1}$
Strip. Line: $y_{\text{strip},n}(x) = \frac{\bar{L}}{\bar{V}}x_{n-1} - \left(\frac{\bar{L}}{\bar{V}} - 1\right)x_B$
$y_{\text{strip}}(x) = ([x_B \cap (y = x)], [q \cap y_{\text{rect}}])$

2.7 Shortcuts for Multicomponent Distillation

2.7.1 Fenske Equation: Minimum Theoretical Stages

$\alpha_{A:B} = \frac{K_A}{K_B} \qquad K_A = \frac{y_A}{x_A}$
$N_{\min} = \ln\left[\left(\frac{x_A}{x_B}\right)_D \left(\frac{x_B}{x_A}\right)_B\right](\ln\alpha_{A:B})^{-1}$
$N_{\min} = \ln\left[\left(\frac{\text{FR}_A}{1-\text{FR}_A}\right)_D \left(\frac{\text{FR}_B}{1-\text{FR}_B}\right)_B\right](\ln\alpha_{A:B})^{-1}$
$N_{\min} = \ln\left[\left(\frac{\text{FR}_{\text{LK}}}{1-\text{FR}_{\text{LK}}}\right)_D \left(\frac{\text{FR}_{\text{HK}}}{1-\text{FR}_{\text{HK}}}\right)_B\right](\ln\alpha_{\text{LK:HK}})^{-1}$
$(\text{FR}_C)_D = (\alpha_{C:B})^{N_{\min}}\left[\left(\frac{\text{FR}_B}{1-\text{FR}_B}\right)_B + (\alpha_{C:B})^{N_{\min}}\right]^{-1}$

2.7.2 Underwood Equations: Minimum Reflux Ratio

$V_{\min} = \sum_i \frac{\alpha_{i:\text{ref}}Dx_{i,D}}{\alpha_{i:\text{ref}} - \phi} \qquad \phi \equiv \frac{L_{\min}}{V_{\min}K_{\text{ref}}}$
$\Delta V_{\text{feed}} = F(1-q) = \sum_i \frac{\alpha_{i:\text{ref}}Fz_i}{\alpha_{i:\text{ref}} - \phi}$
$L_{\min} = V_{\min} - D$
$Dx_{i,D} = Fz_i\text{FR}_{i,D}$
$D = \sum Dx_{i,D}$

2.7.3 Gilliland Correlation: Number of Theoretical Trays

$L/D = C(L/D)_{\min} \qquad 1.05 < C < 1.5$
$x = \frac{L/D - (L/D)_{\min}}{L/D + 1} \qquad y(x) = \frac{N - N_{\min}}{N + 1}$

3 Binary Batch Distillation

$n_F = n_{D,\text{T}} + n_{W,f} \qquad n_Fx_F = n_{D,\text{T}} \cdot \langle x_D \rangle + n_{W,f}x_{W,f}$
Rayleigh: $\ln\frac{n_{W,f}}{n_F} = -\int_{x_{W,f}}^{x_F} \frac{1}{x_D - x_W}dx_W$
$\int_{x_{W,f}}^{x_F} f(x)dx = \frac{x_f - x_{W,f}}{6}\left[f(x_{W,f}) + 4f\left(\frac{x_{w,f}+x_f}{2}\right) + f(x_f)\right]$
$n_{W,f} = n_Fe^{\left[\int_{x_{W,f}}^{x_F} f(x)dx\right]}$

3.1 Steam Batch Distillation

$\Delta n_W = \Delta n_{\text{org}}\frac{P - p_{\text{org}}^\star \cdot \langle x_{\text{vol,org}} \rangle}{p_{\text{org}}^\star \cdot \langle x_{\text{vol,org}} \rangle}$

3.2 Multistage Batch Distillation

$\dot{Q}_{\text{cnd}} = V_1\Delta_{\text{vap}}\hat{H}_1 \qquad \dot{Q}_{\text{rb}} = V_{\text{pot}}\Delta_{\text{vap}}\hat{H}_{\text{pot}}$
$V_1 = V_{\text{pot}} \qquad \Delta_{\text{vap}}\hat{H}_1 = \Delta_{\text{vap}}\hat{H}_{\text{pot}}$
$\dot{Q}_{\text{cnd}} = -\dot{Q}_{\text{rb}} = V\Delta_{\text{vap}}\hat{H}$
$-D\hat{h}_D = \frac{\mathrm{d}(V_{\text{pot}}\hat{h}_{\text{pot}})}{\mathrm{d}t}$

4 Column Design

4.1 Tray Efficiency

$\eta_{\text{overall}} = \frac{\log\left[1 + \eta_{\text{MV}}\left(m_{\text{VLE}}\frac{V}{L} - 1\right)\right]}{\log\left(m_{\text{VLE}}\frac{V}{L}\right)} \qquad m \equiv \text{slope}$

4.2 Column Diameter

$\vec{v}_{\text{flood}} = C_{\text{sb,f}}\left(\frac{\gamma\left[\frac{\text{dyne}}{\text{cm}}\right]}{20}\right)^{0.2}\sqrt{\frac{\rho_L - \rho_V}{\rho_V}}$ [ft/s]
$F_{LV} \equiv \frac{\dot{m}_L}{\dot{m}_V}\sqrt{\frac{\rho_V}{\rho_L}} = \frac{\dot{V}_L}{\dot{V}_V}\sqrt{\frac{\rho_L}{\rho_V}} \qquad C_{\text{sb,f}} \equiv f(F_{LV})$
$0.65 \le \frac{\vec{v}_{\text{operating}}}{\vec{v}_{\text{flood}}} \le 0.9$
$\varnothing_{\text{col}} = \sqrt{\frac{4V\check{m}_V}{\pi\eta_{\text{dc}}\rho_V\vec{v}_{\text{flood}}}}$
$\frac{\check{m}_{V,\text{top}}}{\check{m}_{V,\text{bottom}}}$ often $< 1 \qquad \frac{\rho_{L,\text{top}}}{\rho_{L,\text{bottom}}}$ often $< 1 \qquad \frac{T_{\text{top}}}{T_{\text{bottom}}} < 1$
$\frac{C_{\text{sb,f,top}}}{C_{\text{sb,f,bottom}}} \approx 1 \qquad \frac{\gamma_{\text{top}}}{\gamma_{\text{bottom}}} \approx 1$

4.3 Sieve Tray Layout and Hydraulics

$\vec{v}_{\text{hole}} = \dfrac{\dot{n}_V \check{m}_V}{\rho_V A_{\text{hole}}} \quad A_{\text{hole}} = N_{\text{holes}} \frac{\pi \varnothing_{\text{hole}}^2}{4}$

$A_{\text{dc}} = (1 - \eta_{\text{dc}}) A_{\text{T}} = \frac{R^2(\theta - \sin\theta)}{2} \qquad \{\eta_{\text{dc}} = 0.9\} : \frac{\ell_{\text{weir}}}{\varnothing} = 0.726$

4.4 Valve Tray

$\tilde{H}_{P,\text{valve,closed}} = \dfrac{C_{\text{v}} m_{\text{v}}}{A_{\text{v}} \rho_L} \qquad \tilde{H}_{P,\text{valve,open}} = \dfrac{K_{\text{v}} \rho_V \vec{v}_{\text{hole}}^2}{\rho_L 2g}$

$\vec{v}_{\text{hole, balanced}} = \sqrt{\dfrac{2g C_{\text{v}} m_{\text{v}}}{K_{\text{v}} A_{\text{v}} \rho_V}}$ [Imperial units] $\quad K_{\text{v, closed}} \equiv 5.5$, $K_{\text{v, open}} \equiv 33$, C_{v} dependent on deck

4.5 Packed Column

Height Equivalent of Theoretical Plate $= \frac{100}{\breve{A}} + 0.10$ [m]

$\Delta\tilde{P}_{\text{packing}} = \alpha 10^{\beta \Phi_L} \left(\frac{\Phi_G^2}{\rho_G}\right) \left[\frac{\text{in water}}{\text{ft packing}}\right] \quad \alpha, \beta \equiv$ packing coefficients

$A_{\text{packing}} = \frac{\dot{n}_V \check{m}_V}{\Phi_G}$

$\varnothing \propto (f_{\text{packing}} [\text{ft}^{-1}])^{0.25}$

5 Mass Transport

5.1 Liquid

$\dot{V} = \vec{v} A_\sigma \qquad \dot{V} = \frac{\dot{m}}{\rho}$

$\rho_1 A_{\sigma 1} \langle \vec{v}_1 \rangle = \rho_2 A_{\sigma 2} \langle \vec{v}_2 \rangle$

$\frac{\Delta P}{\rho} + \frac{\Delta(\vec{v}^2)}{2\alpha} + g\Delta z + \sum \hat{F} = \frac{\dot{W}_{\text{s, by}}}{\dot{m}} \qquad \alpha \approx 1$, turbulent; $\alpha = 0.5$, laminar

$z_1 g + \frac{\vec{v}_1^2}{2} + \frac{P_1}{\rho} = z_2 g + \frac{\vec{v}_2^2}{2} + \frac{P_2}{\rho}$

$\eta_{\text{pump}} = \frac{\hat{W}_{\text{s}}}{\hat{W}_{\text{pump}}} \qquad -\hat{W}_{\text{s}} = \tilde{H} g \qquad \text{P}_{\text{brake}} = \frac{-\hat{W}_{\text{s}}}{\eta} \dot{m}$

$\Delta P_{\text{pipe}} = 4 f \rho \dfrac{\ell}{\varnothing} \dfrac{\vec{v}^2}{2} \qquad \Delta P_{\text{pipe,lam}} = \dfrac{32 \mu \vec{v} \ell}{\varnothing^2}$

$\hat{F}_{\text{pipe}} = \dfrac{\Delta P_{\text{pipe}}}{\rho} = 4 f \dfrac{\ell}{\varnothing} \dfrac{\langle \vec{v} \rangle^2}{2} \qquad \hat{F}_{\text{fitting}} = K_{\text{f}} \dfrac{\langle \vec{v} \rangle^2}{2}$

Re$= \frac{\langle \vec{v} \rangle \rho \varnothing}{\mu} \qquad$ Laminar: $f = 16/\text{Re}$

$\text{NPSH}_{\text{A}} = \dfrac{P - p^\star}{\rho g} + z - \tilde{H}_v - \dfrac{\sum \hat{F}}{g} \qquad \tilde{H}_v = \frac{\vec{v}^2}{2g}$

$\dfrac{\dot{V}_1}{\dot{V}_2} = \dfrac{\dot{N}_{\text{r},1}}{\dot{N}_{\text{r},2}} \qquad \dfrac{\tilde{H}_1}{\tilde{H}_2} = \dfrac{\dot{V}_1^2}{\dot{V}_2^2} = \dfrac{\dot{N}_{\text{r},1}^2}{\dot{N}_{\text{r},2}^2} \qquad \dfrac{\dot{W}_1}{\dot{W}_2} = \dfrac{\tilde{H}_1 \dot{V}_1}{\tilde{H}_2 \dot{V}_2} = \dfrac{\dot{N}_{\text{r},1}^3}{\dot{N}_{\text{r},2}^3}$

5.2 Ideal Gas

$\rho = \frac{P \check{m}}{RT} \qquad \gamma = \frac{C_P}{C_V}$

$\{\Delta T = 0\} : -\hat{W}_{\text{s}} = \frac{P_1}{\rho_1} \ln \frac{P_2}{P_1} \qquad \frac{P_1}{\rho_1} = \frac{P}{\rho} = \frac{RT}{\check{m}}$

$\{\Delta Q = 0\}$:

$-\hat{W}_{\text{s}} = \frac{\gamma}{\gamma - 1} \frac{RT_1}{\check{m}} \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$

$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad \frac{P_1}{\rho_1} = \left(\frac{P}{\rho}\right)^\gamma$

Polytropic: $\frac{P_1}{\rho_1} = \left(\frac{P}{\rho}\right)^n$

References

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