Class 14

Separation Tower Design

Typical Design Parameters

Operating Pressures: Typically, 1 – 415 psia
For Temperature Sensitive Materials: Vacuum Distillation (P > 5 mm Hg)
Condensers: Typically Total Condenser (unless low-boiling components)

Combined Manual/Simulator Design Method

1) Estimate the distillate and bottoms compositions and flow rates via a hand material balance and recognizing light and heavy key components
2) Use the graphical algorithm in figure 7.9 (page 249 of text) to establish column pressure and condenser type

Using Distillate Composition

a) use HYSYS to help calculate the estimated bubble point pressure of the distillate, P_D, at 120°F (the idea is to use cooling water which typically exits at 120°F).

b) If this calculated bubble point P_D < 215 psia, use a total condenser; however , if the bubble point P_D < 30 psia, set the condenser outlet pressure at $20 < P_D < 30$ psia to avoid vacuum operation.

c) However, if bubble point P_D > 215 psia, calculate the distillate dew point pressure at 120°F; if that dew point pressure is < 365 psia, use a partial condenser; if the dew point pressure is > 365 psia, select a refrigerant that gives a minimum approach temperature of 5 to 10°F (select this in place of cooling water) for the partial condenser such that the distillate dew point pressure < 415 psia. Up to this point, the tower operating P has been determined by the estimated composition of the distillate.

Checking Bottoms Composition

d) Using the determined condenser outlet pressure from (a) to (c), assume a condenser ΔP of 0 to 2 psia; assume a tower pressure drop of from 5 to 10 psia; hence, a P at the bottom of the column, P_B, will be 5 to 12 psia greater than the condenser outlet pressure (almost all reboilers are partial reboilers that produce a bottoms product at or close to the bubble point).

Algorithm for Establishing Column P and Condenser Type

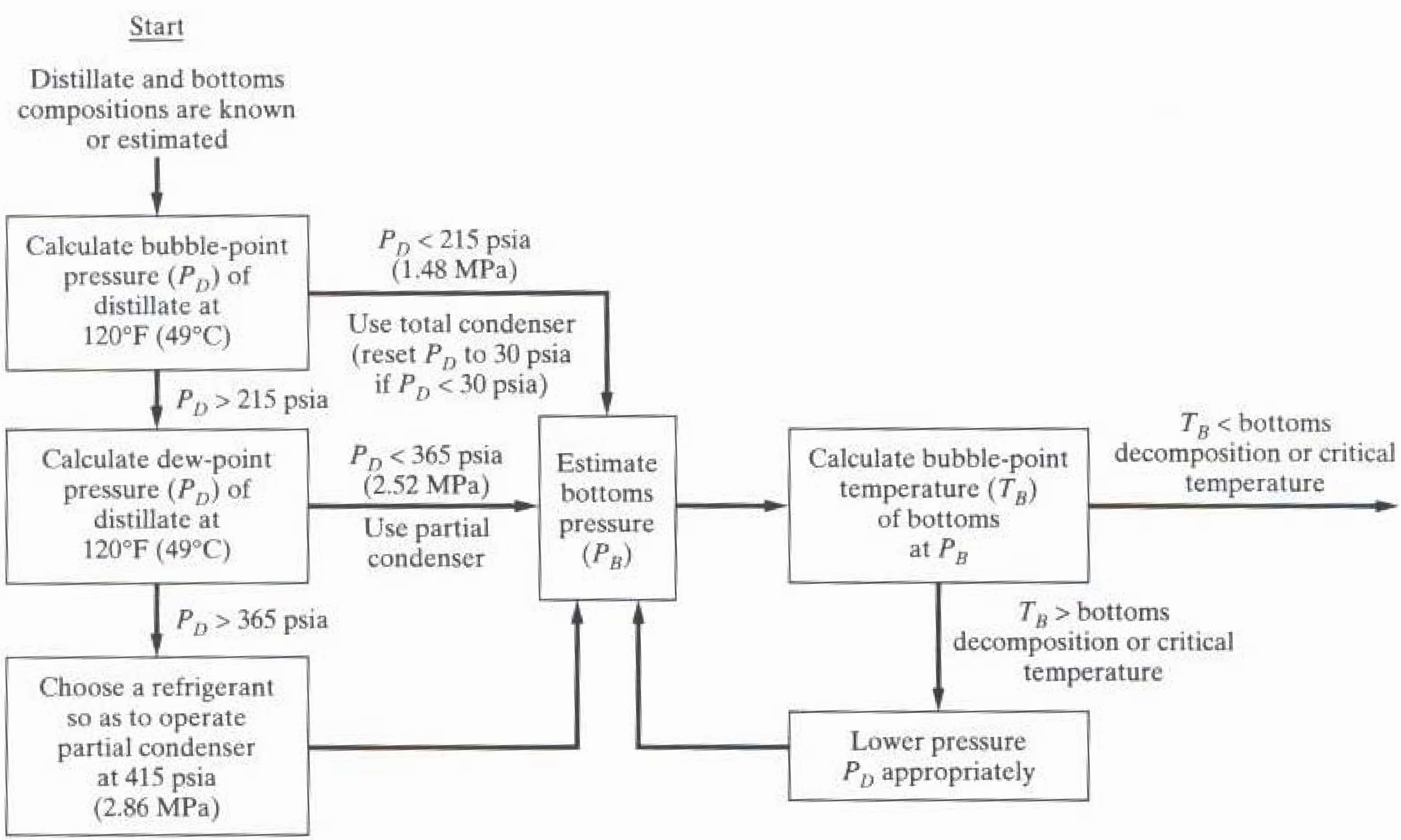


Figure 7.9 Algorithm for establishing distillation column pressure and condenser type.

e) Determine the bottoms temperature, T_B, by a bubble point calculation (using HYSYS) based on the estimated bottoms composition and pressure; if this exceeds the decomposition, polymerization, or critical temperature of the bottoms, then compute the bottoms P based on a bottoms T safely below the limiting T

f) Then, using the assumed ΔP, calculate a new condenser outlet P and T – this may require a change in the coolant used in the condenser and the type of condenser; the new condenser outlet P may be < 15 psia, in which case the tower will be operating under a vacuum

g) For vacuum operations, the vapor distillate is sent to a vacuum pump

3.) Use Fenske Equation to determine the minimum number of equilibrium stages

$$N_{min} = \frac{\ln [x_{LK}/x_{HK})_D (X_{HK}/X_{LK})_B]}{\ln [\alpha_{LK/HK}]_{av}}$$

where x_{LK} = mole fraction of light key component

x_{HK} = mole fraction of heavy key component

$\alpha_{LK/HK\ av}$ = avg geometric relative volatility

$= [(\alpha_{LK/HK})_D (\alpha_{LK/HK})_B]^{1/2}$

D = distillate, B = bottoms products

and using HYSYS to calculate the relative volatility

4.) Use Underwood Equations to determine the minimum reflux ratio, R_{min}

$$\sum_{i=1}^{n} \frac{(\alpha_i)(x_{F,i})}{(\alpha_i - \Theta)} = 1 - q$$

(solve for Θ by trial and error)

n = number of individual components in the feed

α_i = avg geometric relative volatility of component i in the mixture relative to the heavy key component

$x_{F,i}$ = mole fraction of component i in the feed

q = moles of saturated liquid on the feed tray per mole of feed

Θ lies between the relative volatilities of the two key components

Then, solve for the minimum reflux ratio, R_{min}:

$$R_{min} + 1 = \sum_{i=1}^{n} \frac{(\alpha_i)(x_{D,i})}{(\alpha_i - \Theta)}$$

$x_{D,i}$ = mole fraction of component i in the distillate

5) Select a Reflux Ratio that is $R = (1.1 \text{ to } 1.5)\, R_{min}$

6) Use the Gilliland Correlation to calculate the actual number of equilibrium stages, N

$$\frac{N - N_{min}}{N + 1} = 0.75 \left[1 - \left(\frac{R - R_{min}}{R + 1} \right)^{0.566} \right]$$

(note that this equation is a best fit of the curve in Figure 14.1)

7) Use the Kirkbride equation to determine the ratio of trays above and below the feed point:

$$\ln (N_B/N_D) = 0.206 \ln\{(B/D)\ (x_{HK}/x_{LK})_F\ [(x_{LK})_B/(x_{HK})_D]^2\}$$

B = molar flow rate of bottoms
D = molar flow rate of distillate
N_D = number of equilibrium stages above feed tray
N_B = number of equilibrium stages below feed tray

(note: $N = N_D + N_B$ which is solved simultaneously with Kirkbride equation, using N calculated from the Gilliland Correlation)

8) Calculate non-key components if needed to estimate any additional compositions for simulator

$$(x_{D,i}/x_{B,i}) = [(\alpha_i)_{avg}]^{Nmin} [(x_{HK})_D/(x_{HK})_B]$$

where:

$x_{B,i}$ = mole fraction of component i in bottoms
$x_{D,i}$ = mole fraction of component i in distillate
N_{min} = minimum number of stages from Fenske equation
$(\alpha_i)_{avg}$ = average geometric relative volatility of component i relative to heavy key component

Thus, prior to simulation, given a feed stream, we have estimated:

(1) molar flow rates of distillate, D, and bottom, B, via simple material balance assuming a given split (desired split)
(2) column pressure, P, and condenser type via algorithm in Figure 7.9
(3) minimum number of stages, N_{min}, via Fenske equation
(4) minimum reflux ratio, R_{min}, via Underwood equations
(5) selected a reflux ratio, based on multiple of R_{min}
(6) calculated the actual number of equilibrium stages, N from Gilliland Correlation (or Figure 14.1)
(7) calculated the feed stage from the Kirkbride equation
(8) estimated composition for any non-key components in distillate and bottoms

9) Select Column Internals (trays, random or structural packing)

- trays favored for high operating P or liquid flow rate & large column diameter (sieve trays preferred due to low cost; 60 to 85% efficient)

Typical Sieve Tray Geometry

Parameter	Range
Hole diameter, m	0.005–0.025
Fractional free area, m^2	0.06–0.16
Fractional downcomer area, m^2	0.05–0.30
Pitch/hole diameter ratio	2.5–4.0
Tray spacing, m	0.305–0.915
Weir height, m	0.025–0.075

- random packings recommended for small column diameters, corrosion, foaming, or for batch columns (ceramic, metal, or plastic)
- structural packings used for low pressure or vacuum operations; also for low ΔP across column, or low liquid hold-up

Plate Efficiency and HETP
(Height Equivalent to a Theoretical Plate)

<u>Trayed Columns</u>

$$N_{\text{actual plates}} = N_{\text{equilibrium plates}} / E_o$$

(note: $N_{\text{equilibrium plates}}$ = N stages from prior calculations)

Typical E_o = 0.70 for distillation
= 0.50 for strippers
= 0.30 for absorbers

<u>Packed Columns</u>

<u>Random Packings with low viscosity liquids (typical)</u>

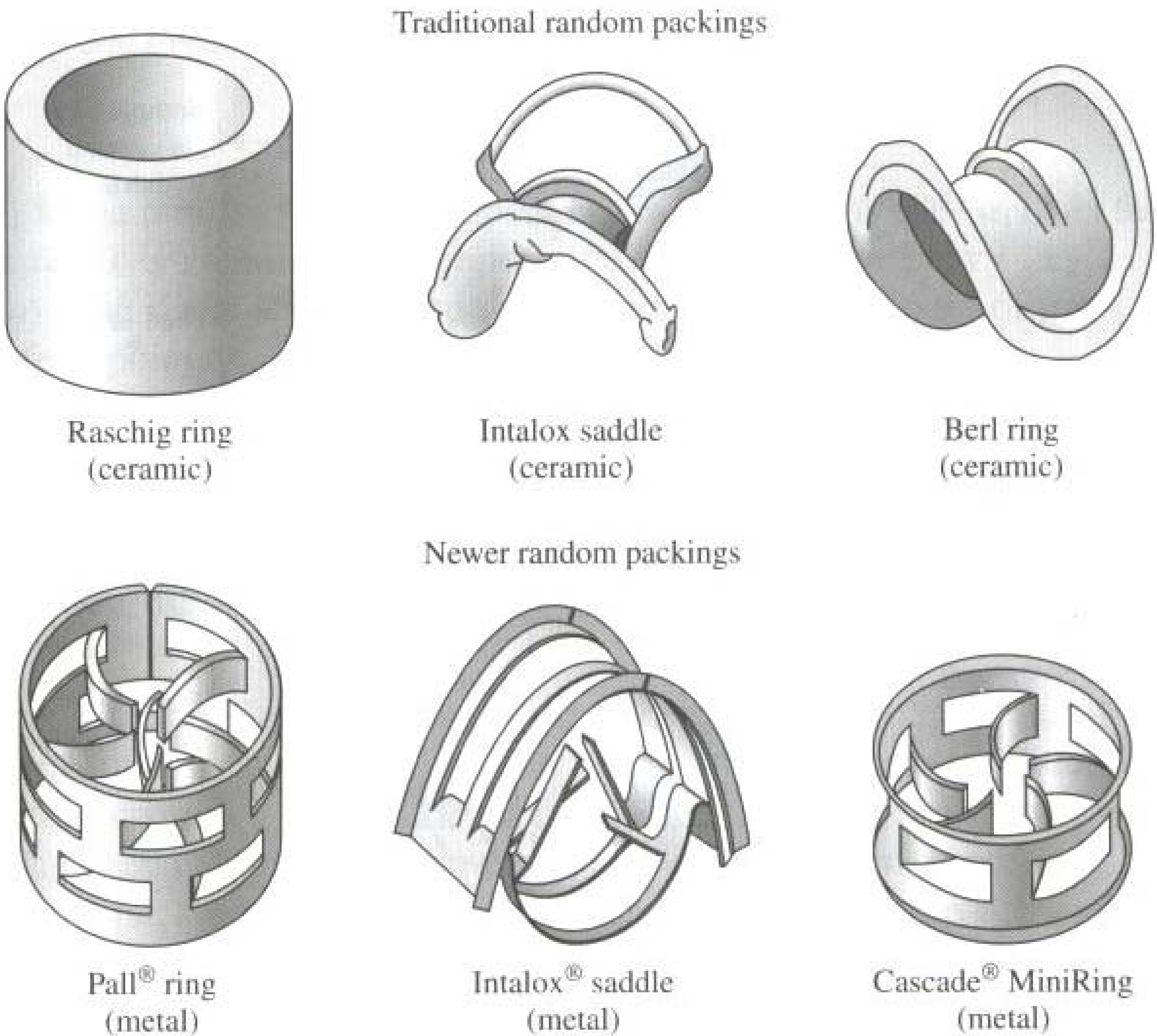
HETP (in feet) = 1.5 (D_p, inches)

(D_p = nominal diameter of a random packing)

<u>For Vacuum Service</u>

HETP (in feet) = 1.5 (D_p, inches) + 0.5

$$\text{Packed height} = N_{\text{equilibrium}} \,(\text{HETP})$$


Traditional random packings
Raschig ring
(ceramic)
Intalox saddle
(ceramic)
Berl ring
(ceramic)
Newer random packings
Pall® ring
(metal)
Intalox® saddle
(metal)
Cascade® MiniRing
(metal)

Geometry and Efficiency of Random Packings

Type of packing	Void fraction	Surface area per volume, m^2/m^3	Approx. HETP, m
25-mm Ceramic Raschig rings	0.73	190	0.6–0.12
25-mm Ceramic Intalox saddles	0.78	256	0.5–0.9
25-mm Ceramic Berl saddles	0.69	259	0.6–0.9
25-mm Plastic Pall rings	0.90	267	0.4–0.5
25-mm Metal Pall rings	0.94	207	0.25–0.3
50-mm Norpac®	0.94	102	0.45–0.6
50-mm Highflow® rings	0.93	108	0.4–0.6

[†]Additional values are available in M. S. Peters and K. D. Timmerhaus, *Plant Design and Economics for Chemical Engineers*, 4th ed., McGraw-Hill, New York, 1991, p. 690.

Geometry and HETP (height equivalent to a theoretical plate) of Some Structural Packings

Type of packing	Void fraction	Surface area per volume, m^2/m^3	Approx. HETP, m
Intalox 2T (Norton)	0.96	213	0.2–0.3
Flexipac® 1 (Koch)	0.91	558	0.2–0.3
Flexipac® 2 (Koch)	0.93	249	0.3–0.4
Gempak® 4A (Glitsch)	0.91	525	0.2–0.3
Gempak® 2A (Glitsch)	0.93	262	0.3–0.4
Sulzer BX (Sulzer)	0.90	499	0.2–0.3

[†]Additional values are available in H. Z. Kister, *Distillation Design*, McGraw-Hill, New York, 1992, p. 446.

9) Calculate Column Diameter

Column Diameter

-Depends on vapor and liquid flow rates and properties up/down column
-Computed to avoid flooding (liquid begins to fill tower & leave with vapor)

Tray Towers
Packed Towers

Tray (Plate) Tower Column Diameter Calculation

- Diameter is calculated to avoid entrainment flooding

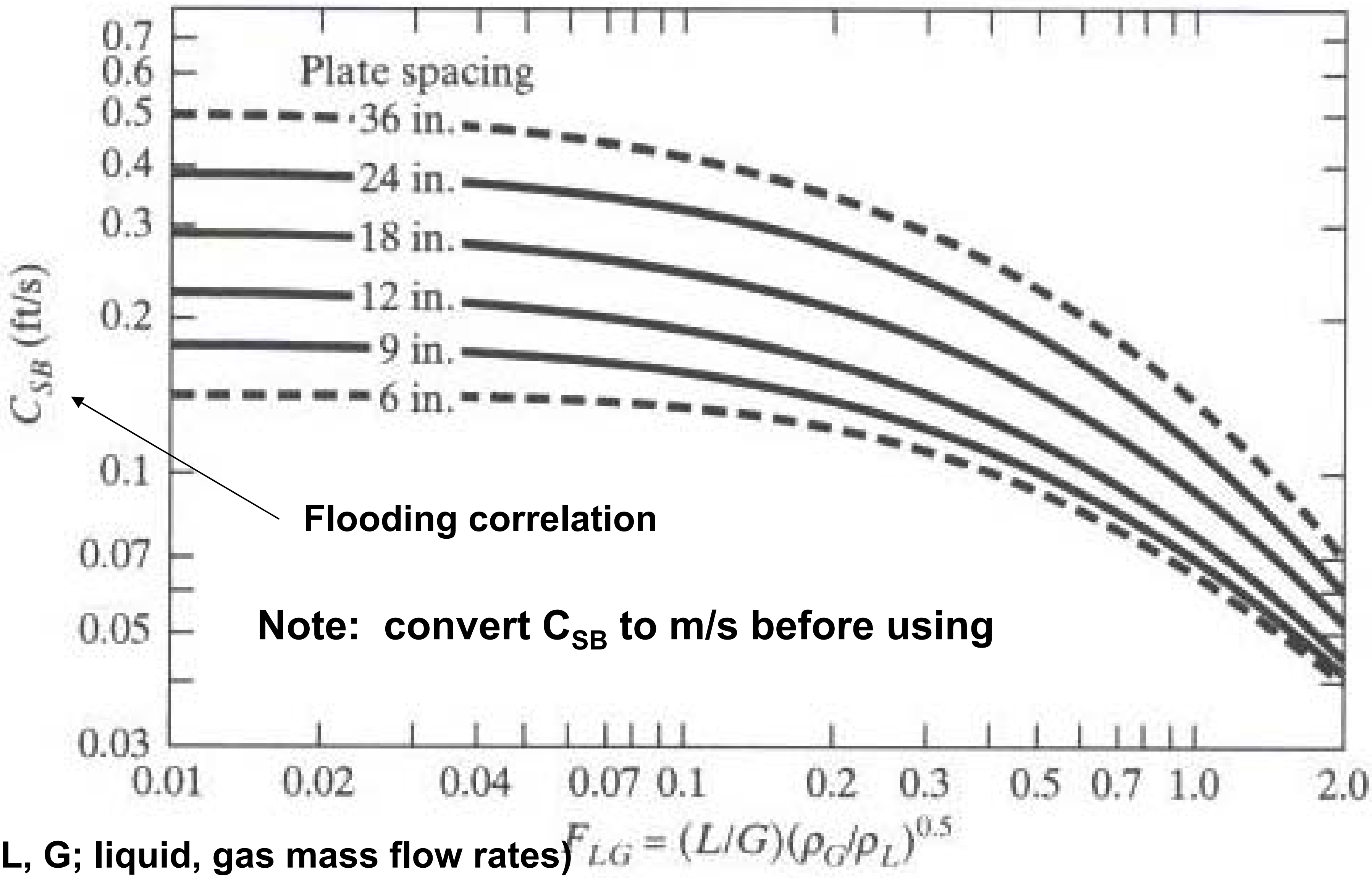
$$D_T = \left[\frac{4G}{(fU_f)\,\pi\,[1 - (A_d/A_T)]\rho_G} \right]^{1/2}$$

Where: G = mass flow rate of vapor (e.g. kg/s)
A_d = downcomer area (e.g. m^2)
ρ_g = vapor density (e.g. kg/m^3)
A_T = tower inside cross-sectional area (e.g. m^2)
f = fraction of the vapor flooding velocity (~ 0.75 to 0.85)
U_f = vapor flooding velocity (e.g. m/s)
D_T = tower diameter (e.g. m)

$$U_f = C[(\rho_L - \rho_G)/\rho_G]$$

ρ_L = liquid density (e.g. kg/m^3)
C = Empirical Capacity Parameter

$C = C_{SB}\, F_{ST}\, F_F\, F_{HA}$



(L, G; liquid, gas mass flow rates)

Flooding Correlation for Sieve Valve, and Bubble-cap trays

F_{ST} = surface tension factor = $(\sigma/20)^{0.20}$

where σ is surface tension in (dyne/cm)

F_F = foam factor (=1 typical for distillation systems;

= 0.5 to 0.75 for foaming systems)

F_{HA} = hole factor (=1 for valve and bubble-cap trays;

=1 for sieve trays for $(A_h/A_a > 0.10)$

= $[5(A_h/A_a) + 0.5)]$ for $0.06 < (A_h/A_a) < 0.1)$

where A_h = hole area of tray

A_a = active area of tray = $(A_T - 2A_d)$

where bubbling occurs

A_d, downcomer area

A_T, tower inside cross-sectional area

$$\frac{A_d}{A_T} = \begin{cases} 0.1, & F_{LG} \le 0.1 \\ 0.1 + \dfrac{(F_{LG} - 0.1)}{9}, & 0.1 \le F_{LG} \le 1.0 \\ 0.2, & F_{LG} \ge 1.0 \end{cases}$$

Packed Tower Column Diameter Calculation

The diameter of a packed tower is calculated from an estimated flooding velocity with a continuity equation similar to that for a tray tower:

$$D_T = \left[\frac{4G}{(fU_f)\,\pi\,\rho_g} \right]^{1/2}$$

Where: G = mass flow rate of vapor (e.g. kg/s)
ρ_g = vapor density (e.g. kg/m^3)
f = fraction of the vapor flooding velocity (~ 0.7 for packed tower)
U_f = vapor flooding velocity (e.g. m/s)
D_T = tower diameter (e.g. m)

U_f for packed towers calculated from generalized correlation

$$Y = \exp[-3.7121 - 1.0371 (\ln F_{LG}) - 0.1501 (\text{in } F_{LG})^2 - 0.007544 (\ln F_{LG})^3]$$

Y is dimensionless

Flow Ratio Parameter: $F_{LG} = (L/G)(\rho_G/\rho_L)^{1/2}$

$$f\{\rho_L\} = -0.8787 + 2.6776 (\rho_{H2O(l)} / \rho_L) - 0.6313 (\rho_{H2O(l)} / \rho_L)^2$$

for density ratios $(\rho_{H2O(l)} / \rho_L)$ from 0.65 to 1.4

$f\{\mu_L\} = 0.96 (\mu_L^{0.19})$ for liquid viscosities from 0.3 to 20 cP and random packings of 1 inch nominal diameter or more

$$U_f = \left[\frac{(Y)(g)\ (\rho H2O(l)\ /\ \rho G)}{F_p\ f\{\rho L\}\ f\{\mu L\}} \right]^{1/2}$$

Important (units)!

g = 32.2 ft/s^2
Y = 0.01 to 10 from correlation
U_f = flooding velocity (ft/s)
F_p packing factor in (ft^2/ft^3) from Table 14.1

(Tower inside diameter should be at least 10 times nominal packing diameter and preferably closer to 30 times)

Table 14.1 Packing Factors for Calculating Flooding Velocity

Type Packing	Material	Nominal Diameter, D_P (in.)	Packing Factor, F_P (ft^2/ft^3)
Raschig rings	Ceramic	1.0	157
		2.0	58
		3.0	33
Raschig rings	Metal	1.0	165
		2.0	71
		3.0	40
Intalox saddles	Ceramic	1.0	92
		2.0	30
		3.0	15
Intalox saddles	Plastic	1.0	36
		2.0	25
Pall rings	Metal	1.0	56
		1.5	29
		2.0	27
		3.5	16
Pall rings	Plastic	1.0	53
		2.0	25
		3.5	15