CE 407 Notes
Binary distillation nearly pure products examples

Example 1(a)

Example. 120 mol/h of a feed solution with composition 65 mole percent benzene, 35 mole percent toluene is to be fractionated to produce distillate with toluene mole fraction equal to 0.0006 and bottom product with benzene mole fraction equal to 0.02. At a reflux ratio $R = 2.0$, and assuming ideal stages, how many stages will be required if the feed enters as saturated liquid and a total condenser is used?
Partial solution. The operating line for the rectifying section is given by

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1} = 0.666667 x_n + 0.333133$$

(since $x_D = 0.9994$ and $R = 2.0$). Two points on the equilibrium curve are $(x, y) = (1, 1)$ (obvious) and $(x, y) = (0.90, 0.96)$. These correspond to the linear relation

$$y = 0.40x + 0.60,$$

which approximates the pure-benzene end of the equilibrium curve.
To reach the cross-section where $x_N = x_b = 0.9$ one would set

$$\begin{aligned} y_a &= x_D = 0.9994, \\ y_a^\star &= y^\star(x_a) = 0.40\, x_a + 0.60 = 0.99976, \\ y_b &= y_{N+1} = 0.666667\, x_N + 0.333133 = 0.933133, \\ y_b^\star &= y^\star(x_b) = 0.96. \end{aligned}$$

Then

$$N = \frac{\log\left(\frac{y_b - y_b^\star}{y_a - y_a^\star}\right)}{\log\left(\frac{y_b - y_a}{y_b^\star - y_a^\star}\right)} = \frac{\log\left(\frac{0.933133 - 0.96}{0.9994 - 0.99976}\right)}{\log\left(\frac{0.933133 - 0.9994}{0.96 - 0.99976}\right)} = 8.4.$$

Thus, one could start stepping from the point on the operating line where $x = 0.9$, keeping in mind that at the very end one must add 8.4 trays to the total from the graph.

Example 1(b)

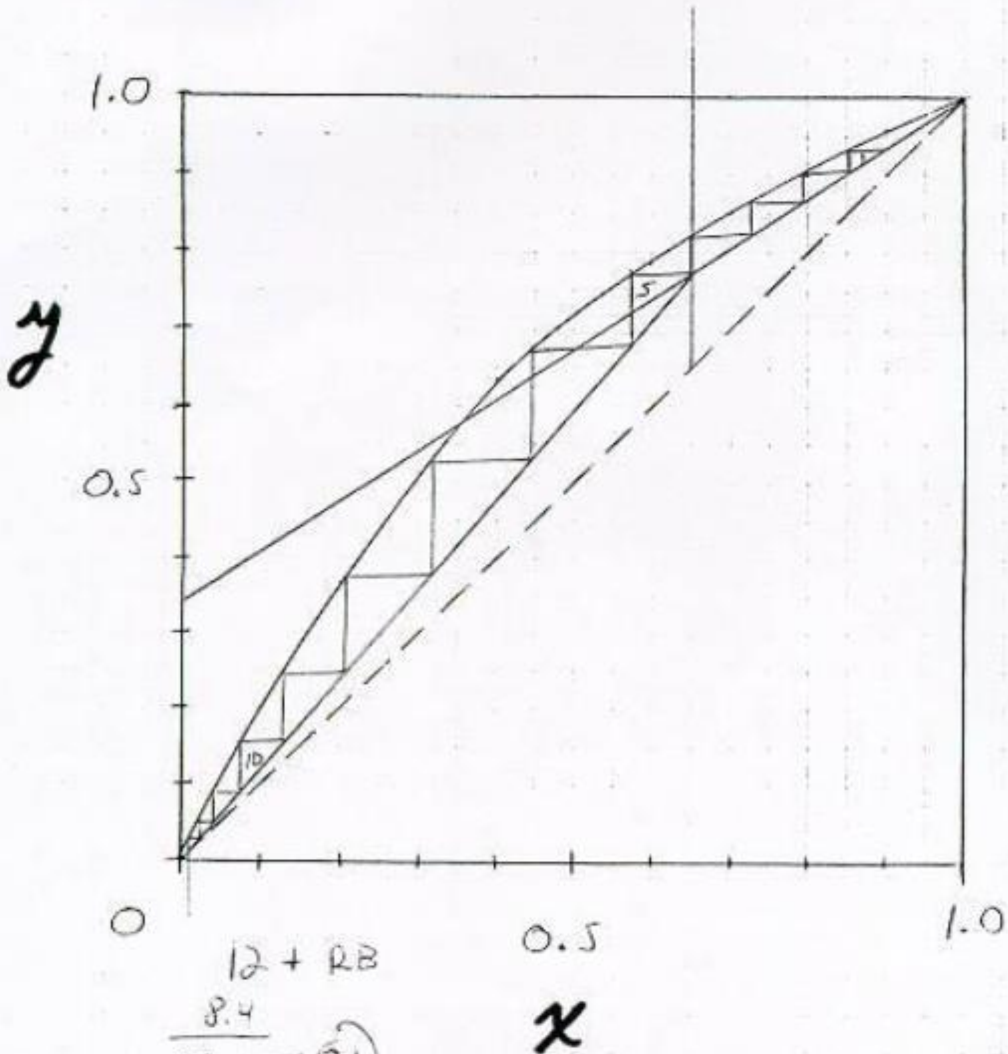
Example. 120 mol/h of a feed solution with composition 65 mole percent benzene, 35 mole percent toluene is to be fractionated to produce distillate with toluene mole fraction equal to 0.0006 and bottom product with benzene mole fraction equal to 0.02. At a reflux ratio $R = 2.0$, and assuming a Murphree efficiency of 60 percent for all stages, how many stages will be required if the feed enters as saturated liquid and a total condenser is used?
Partial solution. Same as above, except now effective equilibrium values have to be used:

$$\begin{aligned} y_a^{\star\prime} &= y_a + 0.60\,(y_a^\star - y_a) = 0.9994 + 0.60(0.99976 - 0.9994) = 0.999616, \\ y_b^{\star\prime} &= y_b + 0.60\,(y_b^\star - y_b) = 0.933133 + 0.60(0.96 - 0.933133) = 0.949253. \end{aligned}$$

Then

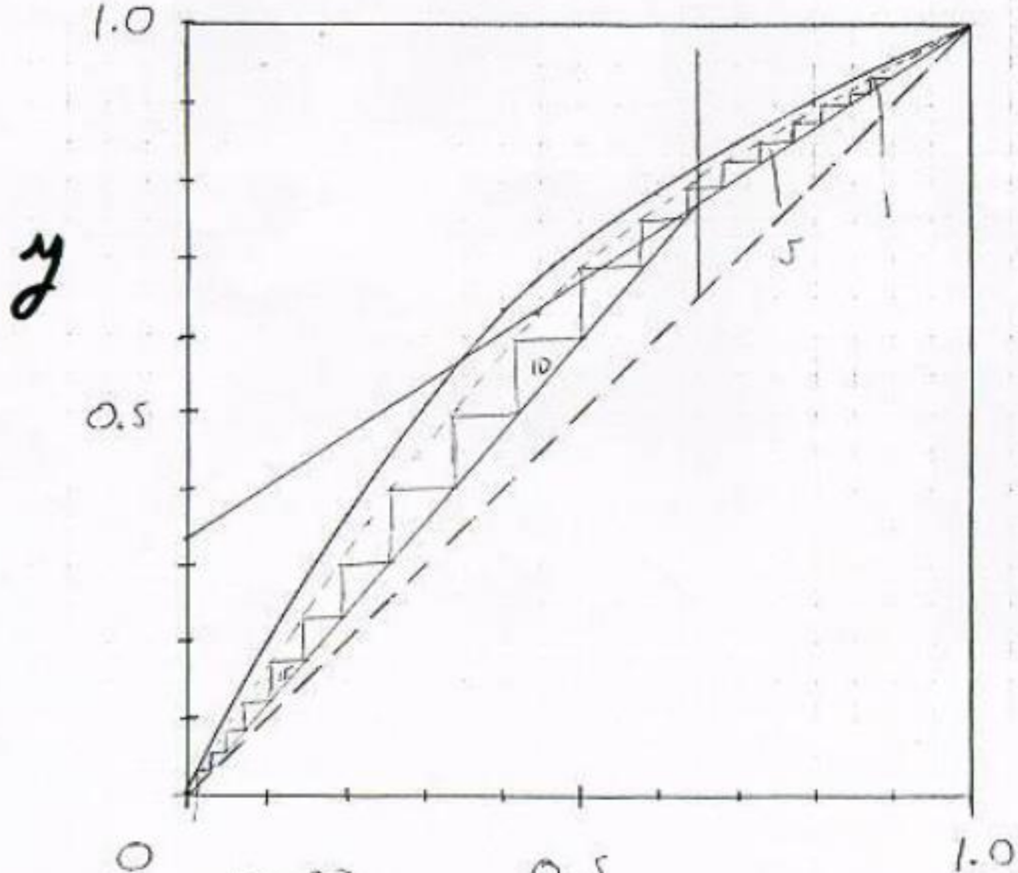
$$N = \frac{\log\left(\frac{y_b - y_b^{\star\prime}}{y_a - y_a^{\star\prime}}\right)}{\log\left(\frac{y_b - y_a}{y_b^{\star\prime} - y_a^{\star\prime}}\right)} = \frac{\log\left(\frac{0.933133 - 0.949253}{0.9994 - 0.999616}\right)}{\log\left(\frac{0.933133 - 0.9994}{0.949253 - 0.999616}\right)} = 15.7.$$

Thus, one could start stepping from the point on the operating line where $x = 0.9$, keeping in mind that at the very end one must add 15.7 trays to the total from the graph.



12 + RB

$\frac{8.4}{20.4} \Rightarrow 21$



x

$18 + RB$

$\frac{15.7}{33.7} \Rightarrow 34$

$\frac{21}{34} = 0.62$

Example 2

Example. An 80 mol/h feed stream with composition 45 mole % methanol ("light"), 55 mole % water ("heavy") is to be separated by continuous distillation in a sieve-plate column fitted with with a total condenser. The distillate should have methanol mole fraction equal to 0.9999 and the bottom product should have water mole fraction equal to 0.98. Feed eners as saturated liquid. All plates have Murphree efficiencies equal to 0.67. If the reflux ratio used is 1.5 times the minimum, how many plates will be required? Equilibrium data are given in the following table. Use the absorption factor method (Kremser equation; either one of Eqs. (20.24) or (20.27)) for $x \geq 0.7$, and the graphical mcCabe-Thiele method for $x \leq 0.7$.

Vapor–liquid equilibrium data for methanol–water mixtures at atmospheric pressure

x	y
0.0	0.000
0.1	0.417
0.2	0.579
0.3	0.669
0.4	0.729
0.5	0.780
0.6	0.825
0.7	0.871
0.8	0.915
0.9	0.959
1.0	1.000

$x_F = 0.45$, $x_D = 0.9999$, $x_B = 1-0.98 = 0.02$

Sat. liquid feed $\Rightarrow q=1$. $R = (1.5)\,R_{min}$. $\eta_M = 0.67$

(i) $\underline{R_{min}}$

Op. line for rectifying section passes through point $(x_D, x_D) = (0.9999, 0.9999)$ (essentially indistinguishable from upper right corner). Feed line passes through point $(x_F, x_F) = (0.45, 0.45)$ and is vertical because $q=1$. From graph,

$$\text{intercept} = \frac{x_D}{R_{min}+1} = 0.55$$

$$\Rightarrow R_{min} = \frac{x_D}{0.55} - 1 = \frac{0.9999}{0.55} - 1 = 0.818$$

(ii) <u>actual column operation</u>

$R = 1.5\,R_{min} = (1.5)(0.818) = 1.227$

1. <u>Op. line for rectifying section</u>:

Passes through $(x_D, x_D) = (0.9999, 0.9999)$ (essentially indistinguishable from upper right corner) and has intercept $x_D/(\underset{1.227}{R}+1) = 0.449$. Draw on graph.

2. <u>Feed line</u>: already drawn

3. <u>Op. line for stripping section</u>

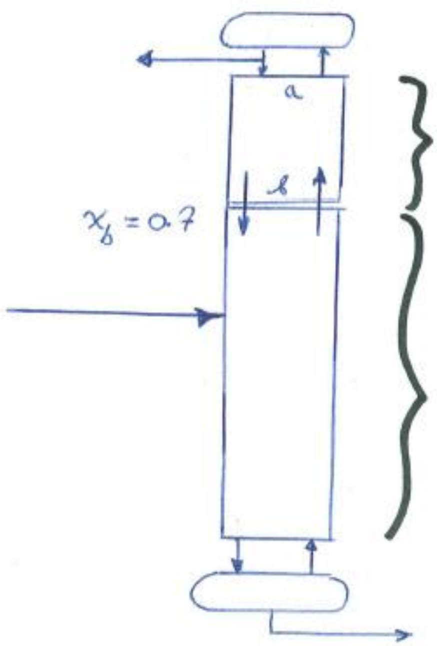
Passes through $(x_B, x_B) = (0.02, 0.02)$ and the intersection of feed line and op. line for rectifying section. Draw on graph.

4. Count steps.

HEY!

Near the upper right corner it's too small to see!! What to do??!

How about dividing the whole column into two parts — the part below the point where $x = 0.7$ (say) and the part above which $x = 0.7$. Determine the number of stages for each part and then add the results.



use Kremser equation

do graphically

4. (lower)

Because $\eta_M = 0.67$, sketch in effective equilibrium curve ~ two thirds of the way up from the operating lines to the equil. curve (see dashed curve in graphs). Then count steps. Note that η_M does NOT apply to reboiler so use actual equil. curve for last step. Need 9 stages for this section.

4. (upper)

Think of this as an absorber with terminal concentrations (x_a, y_a) and (x_b, y_b).

Op. line is 1.227

$$y_{n+1} = \frac{R}{R+1} x_n + \frac{x_D}{R+1} = 0.550965\, x_n + 0.448990 \qquad (1)$$

Approx. equil. curve as straight line passing through the points (0.7, 0.871) and (1,1) or

$$y = 0.43\, x + 0.57 \qquad (2)$$

Now

$y_a = 0.9999$ (don't need to use eq. (1) with $x_n = x_a = 0.9999$ because we already know that when $x_n = x_D$, $y_{n+1} = x_D$.)

$$y_a^* = y^*(x_a) = (0.43)(0.9999) + 0.57$$
$$= 0.999957 \text{ by eq. (2)}$$

$$y_b = (0.550965)\underbrace{(0.7)}_{x_b} + 0.448990 = 0.834666 \text{ by Eq.(1)}$$

$$y_b^* = y^*(x_b) = (0.43)(0.7) + 0.57 = 0.871 \text{ by Eq.(2)}$$

Because of <u>Murphree efficiency</u>, have to use <u>effective equil. values</u>:

$$y_a^{*\prime} = y_a + \eta_M(y_a^* - y_a)$$
$$= 0.9999 + (0.67)(0.999957 - 0.9999)$$
$$= 0.999938$$

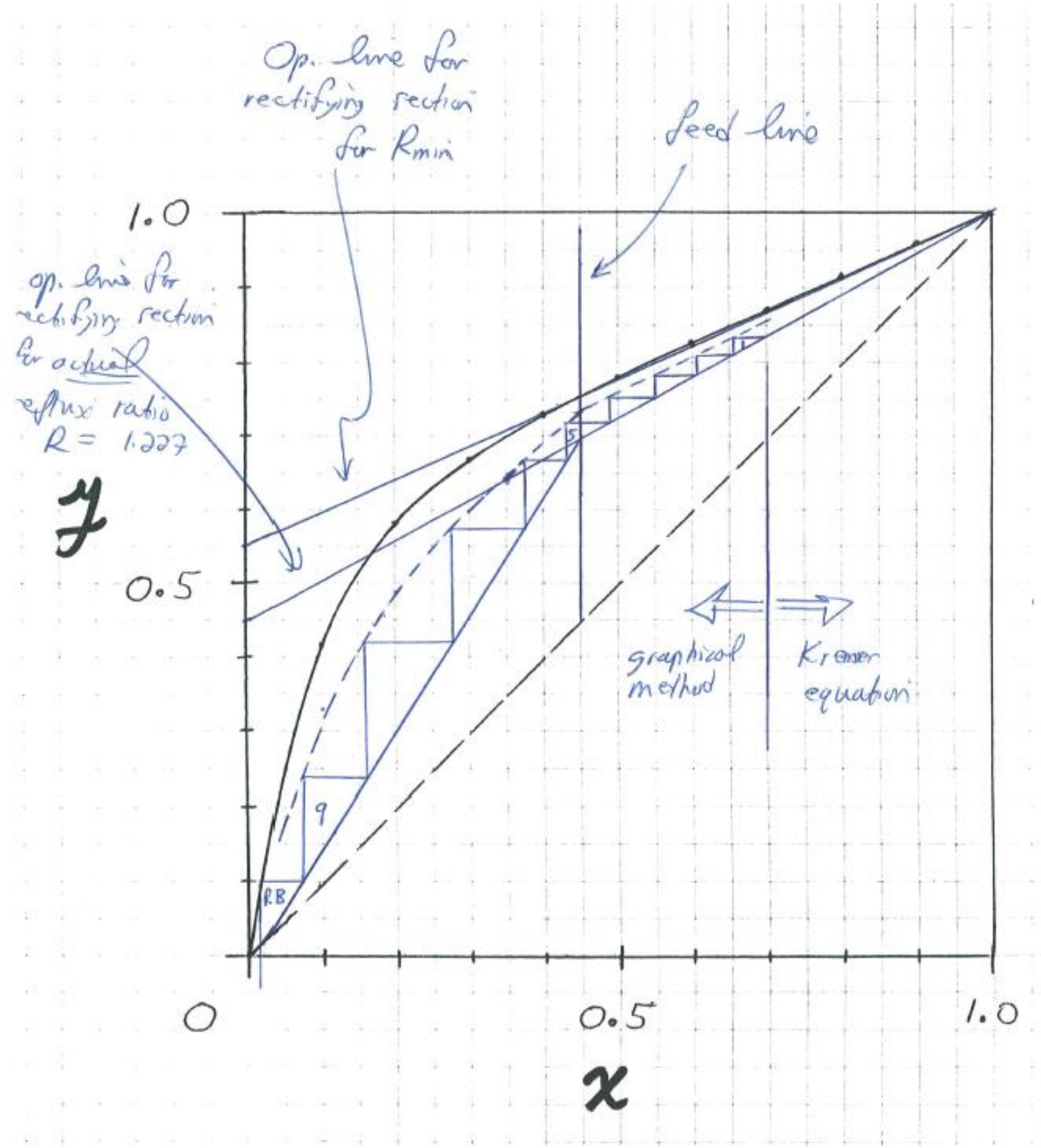
$$y_b^{*\prime} = y_b + \eta_M(y_b^* - y_b)$$
$$= 0.834666 + (0.67)(0.871 - 0.834666)$$
$$= 0.859010$$

Now use Kremser equation (Eq.(17.27) on p.514):

$$N = \frac{\ln\left(\frac{y_a - y_a^{*\prime}}{y_b - y_b^{*\prime}}\right)}{\ln\left(\frac{y_b^{*\prime} - y_a^{*\prime}}{y_b - y_a}\right)} = \frac{\ln\left(\frac{0.9999 - 0.999938}{0.834666 - 0.859010}\right)}{\ln\left(\frac{0.859010 - 0.999938}{0.834666 - 0.9999}\right)}$$

$$= 40.6 \text{ plates}$$

<u>altogether</u> Need $9 + 40.6 = 49.6 \Rightarrow \boxed{50 \text{ plates}}$ (round up)



Op. line for rectifying section for R_{min}
feed line
op. line for rectifying section for actual reflux ratio $R = 1.227$
1.0
0.5
0
0.5
1.0
y
x
5
9
RB
graphical method
Kremser equation