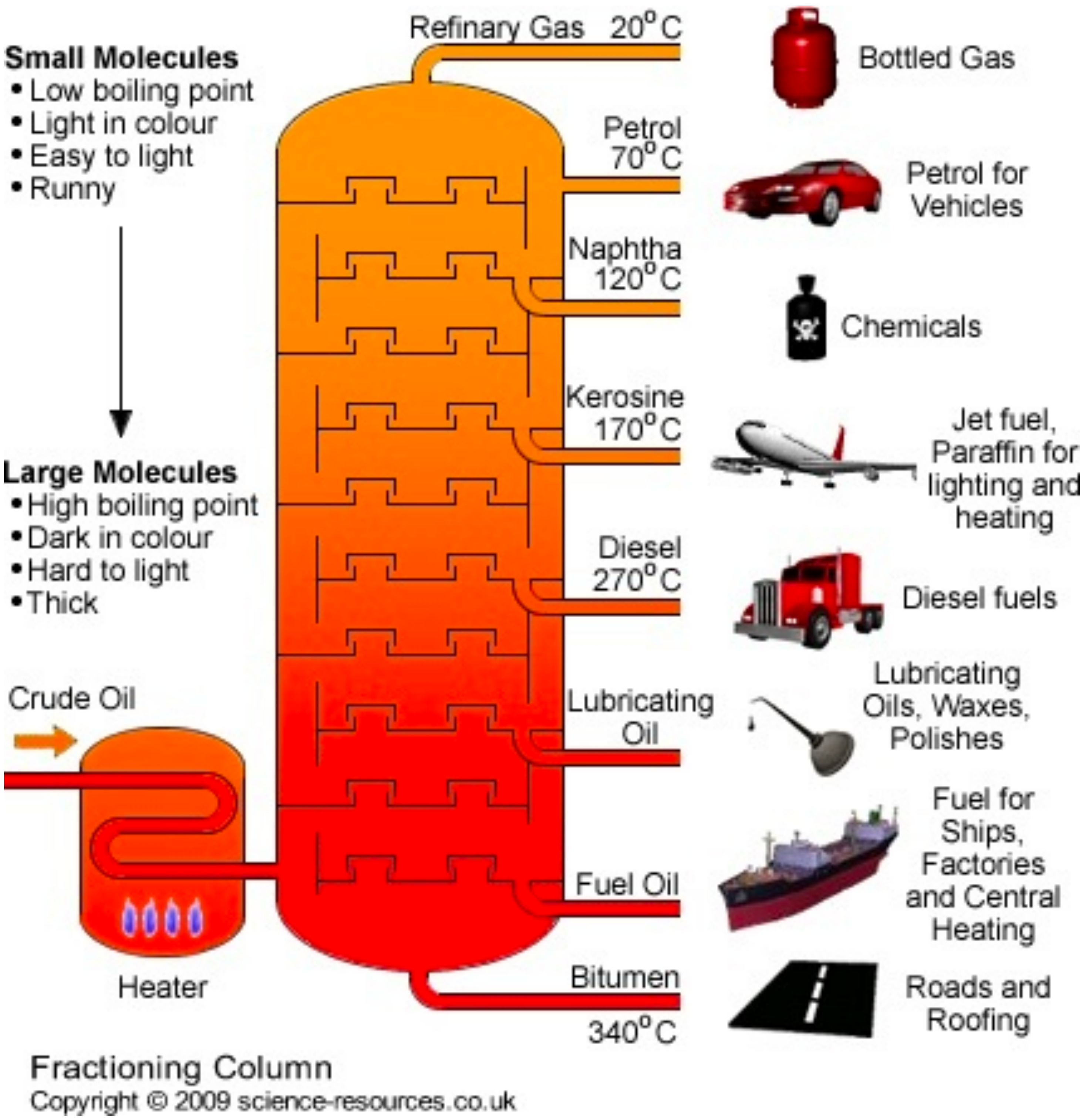
Lecture 5
Multicomponent distillation

Multicomponent distillation



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Intended Learning Outcome:

1. To calculate minimum number of stages (N_{min}) as a function of desired fractional recovery.
2. To calculate minimum reflux ratio (R_{min})
3. To calculate needed number of stages based on a given reflux ratio.

Important notation in multicomponent distillation

Not all component are specified in the distillate and the bottoms

1. Components that are specified are called keys.
2. Components that are not specified are called non-keys (NK).
3. Most volatile of the keys is called light key (LK).
4. Least volatile of the keys is called heavy key (HK).
5. In some cases, we have a light non-key (LNK), when a NK is more volatile than LK.
6. In some cases, we have a heavy non-key (HNK), when a HNK is less volatile than HK.

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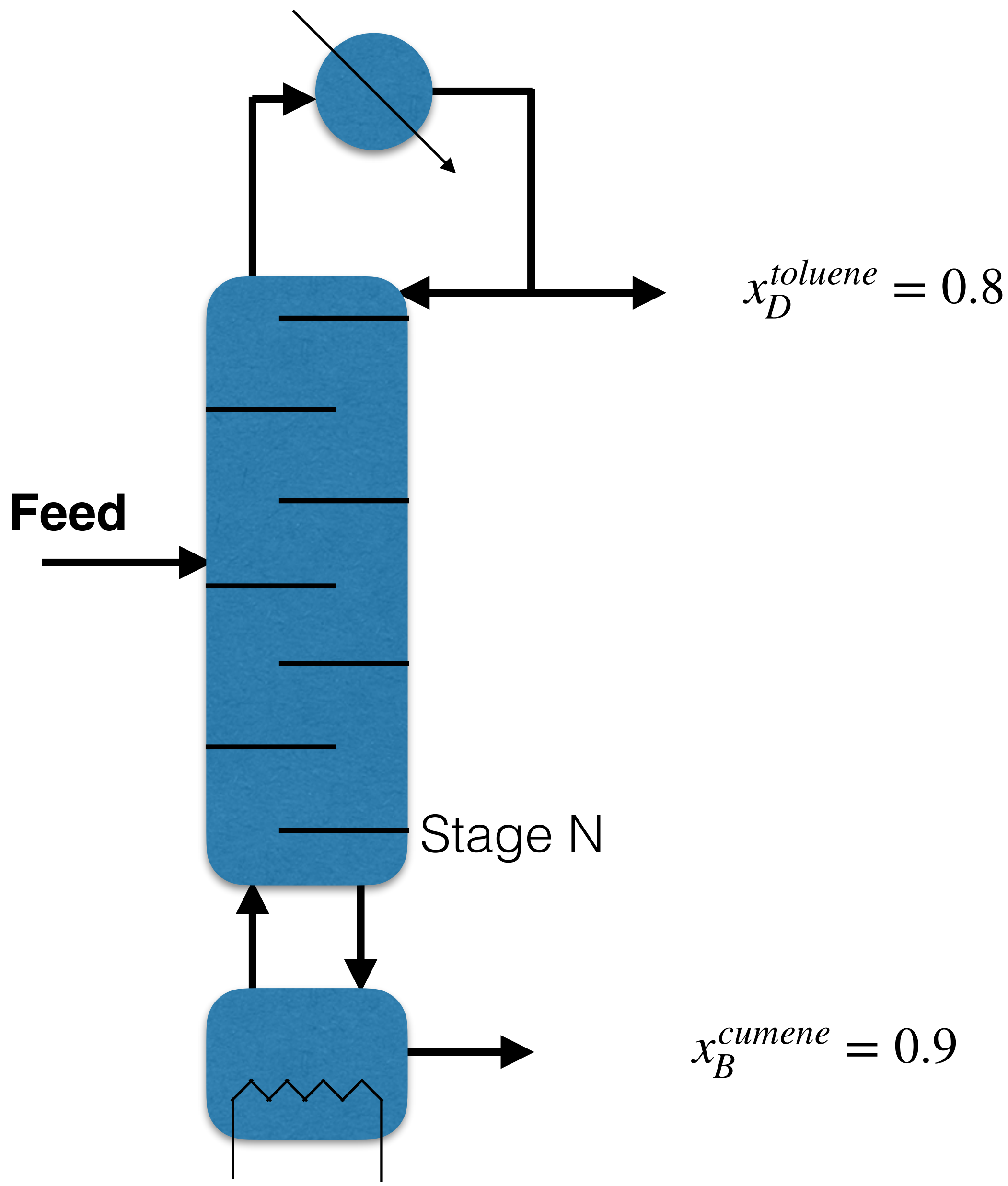
Problem Statement

Which component is LK

A) Cumene
B) Toluene
C) Benzene
D) None of the above

		% in feed
Benzene	80.1 °C	20%
Toluene	110. 6 °C	50%
Cumene	152.4 °C	30%



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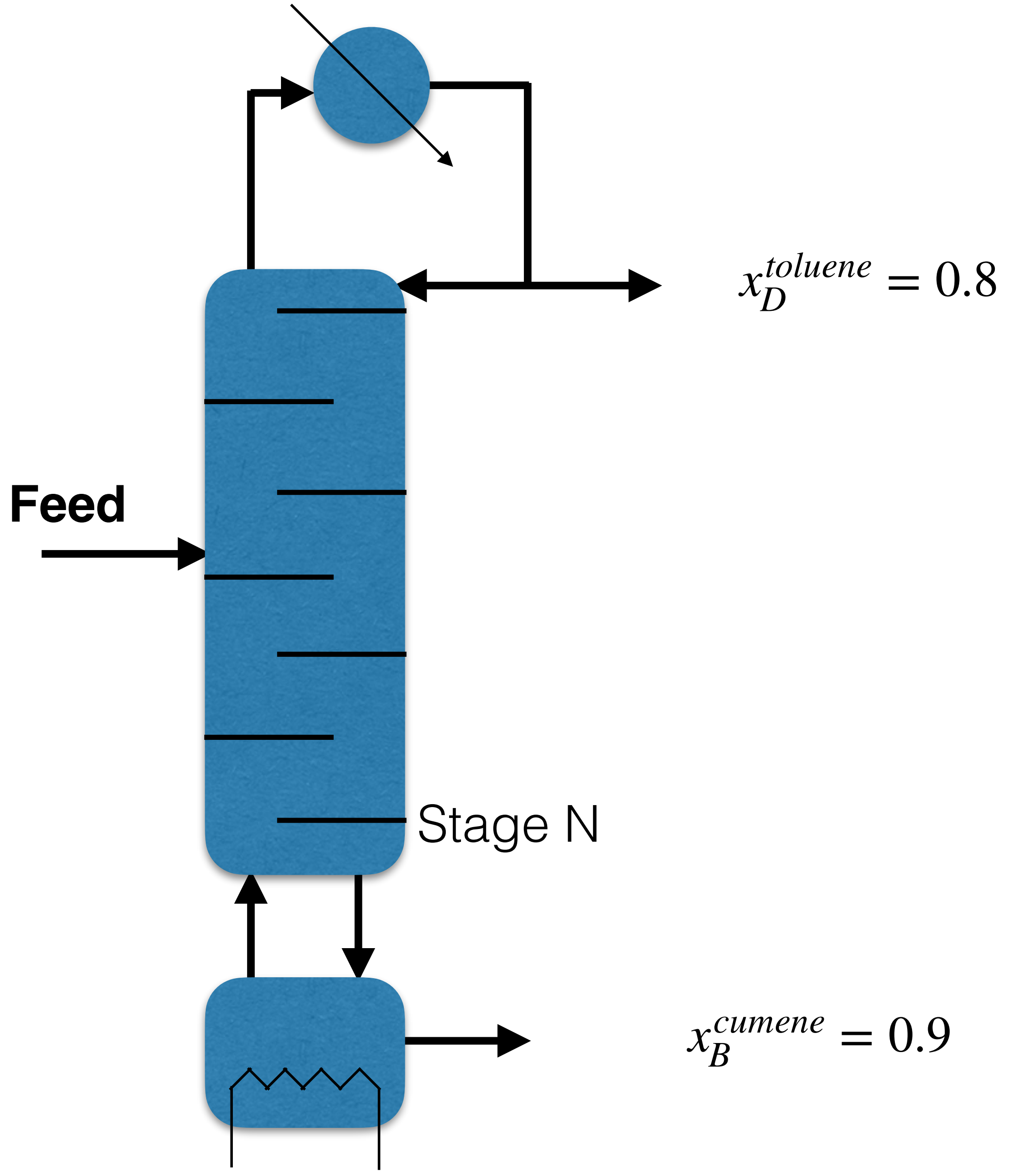
Problem Statement

Which statement is false

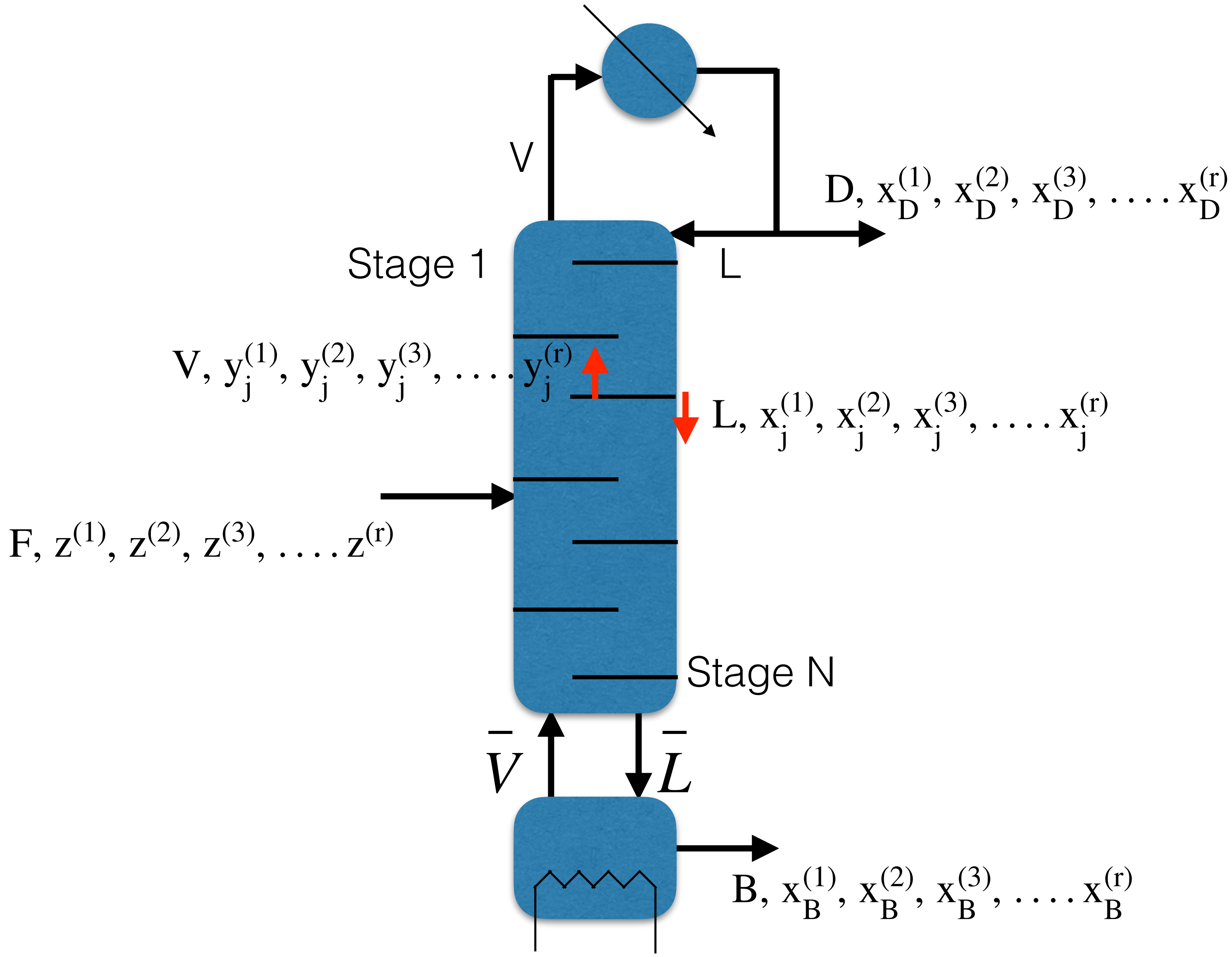
A) NK = Benzene
B) NK = LNK
C) NK = HNK

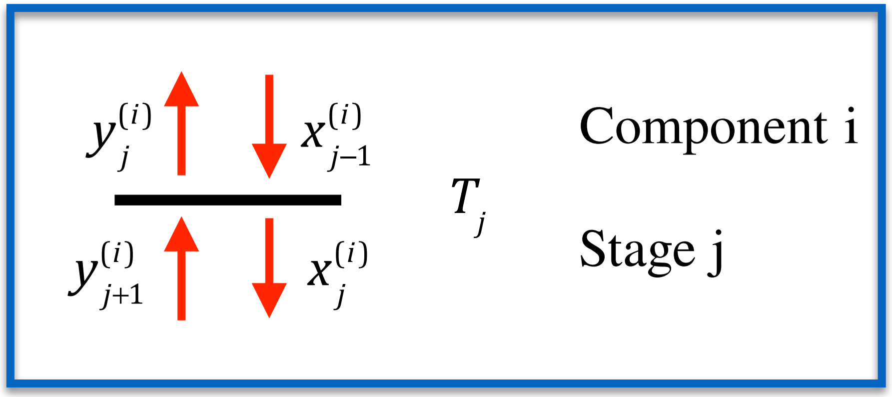
		% in feed
Benzene	80.1 °C	20%
Toluene	110. 6 °C	50%
Cumene	152.4 °C	30%



Multicomponent distillation for r component

Notation:
Subscript refers to position in distillation column.
Superscript refers to component #





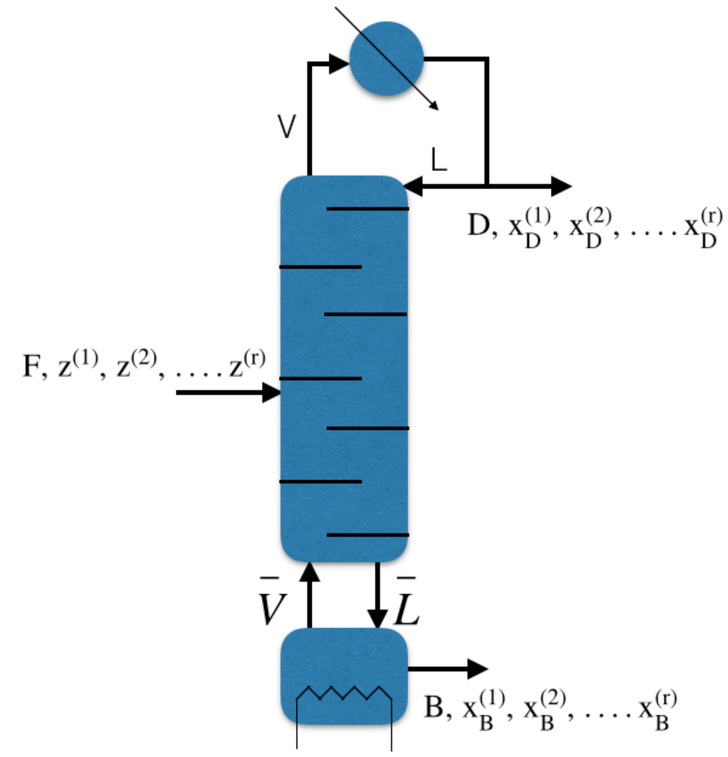
The concept of fractional recovery, FR

Fractional recovery of component 1 in distillate = $\dfrac{\textbf{Amount of component 1 in distillate}}{\textbf{Amount of component 1 in feed}}$

$$FR_D^{(1)} = \frac{Dx_D^{(1)}}{Fz^{(1)}}$$

Fractional recovery of component 1 in bottom = $\dfrac{\textbf{Amount of component 1 in bottom}}{\textbf{Amount of component 1 in feed}}$

$$FR_B^{(1)} = \frac{Bx_B^{(1)}}{Fz^{(1)}}$$



$$FR_D^{(1)} + FR_B^{(1)} = 1$$

$$\frac{FR_D^{(1)}}{FR_B^{(1)}} = \frac{Dx_D^{(1)}}{Bx_B^{(1)}}$$

$$\frac{FR_D^{(1)}}{1 - FR_D^{(1)}} = \frac{Dx_D^{(1)}}{Bx_B^{(1)}}$$

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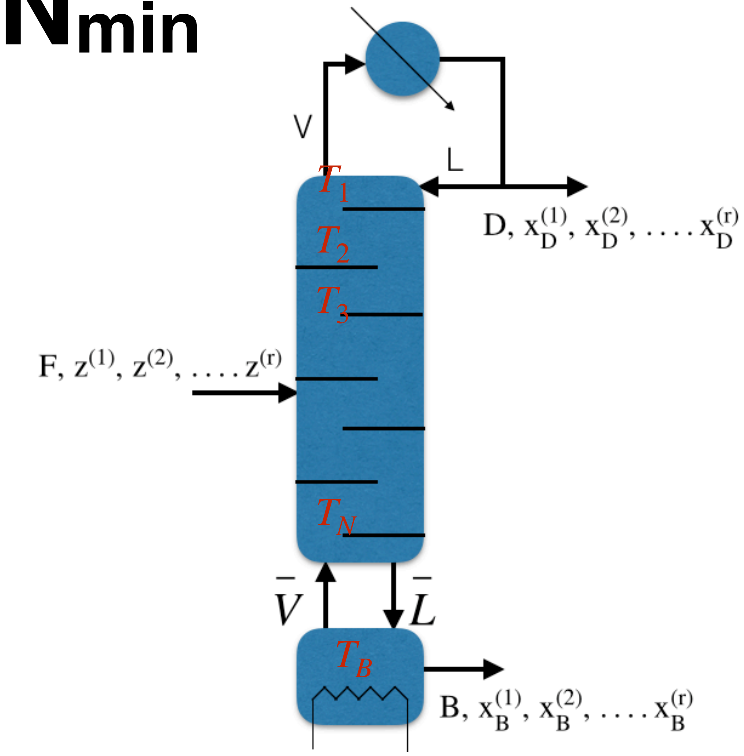
Minimum number of stages: N_{min}

Condition for N_{min} is: $R \to \infty,\ D \to 0,\ B \to 0,\ F \to 0$



Can we establish relationship between $x_D^{(i)}$ and $x_B^{(i)}$

At stage 1: $y_1^i = x_D^i$

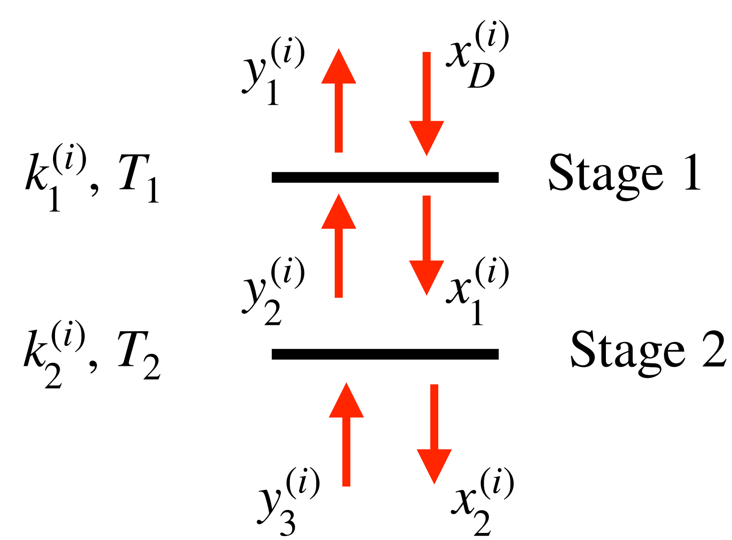
y_1^i is in equilibrium with x_1^i $\Rightarrow y_1^i = k_1^{(i)} x_1^i$ $\Rightarrow x_D^i = k_1^{(i)} x_1^i$

Operating equation for stage 1:

$V = L + D$ $\Rightarrow V = L$

$Vy_2^i = Lx_1^i + Dx_D^i$ $\Rightarrow y_2^i = \frac{L}{V}x_1^i + \frac{D}{V}x_D^i$ $\Rightarrow y_2^i = x_1^i$

Component i



y_2^i is in equilibrium with x_2^i $\Rightarrow y_2^i = k_2^{(i)} x_2^i$ $\Rightarrow x_1^i = k_2^{(i)} x_2^i$

$$\Rightarrow x_D^i = k_1^{(i)} k_2^{(i)} x_2^i$$

$$\Rightarrow x_D^i = k_1^{(i)} k_2^{(i)} k_3^{(i)} \ldots . k_{N-1}^{(i)} k_N^{(i)} k_B^{(i)} x_B^i$$

F=0, so no changes at feed plate

$$x_D^j = k_1^{(j)} k_2^{(j)} k_3^{(j} \ldots . k_{N-1}^{(j)} k_N^{(j)} k_B^{(j)} x_B^j$$

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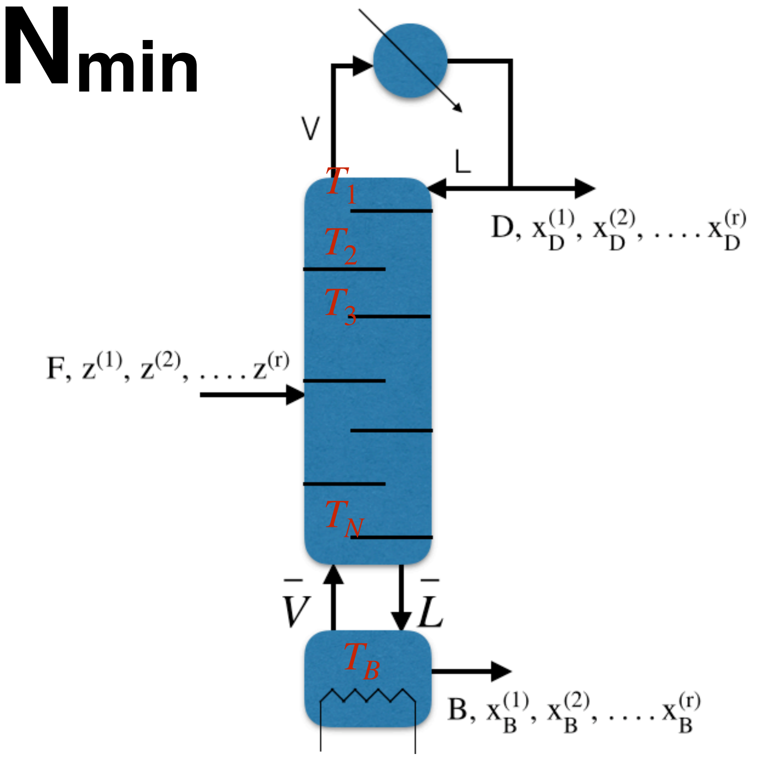
Minimum number of stages: N_{min}



$$x_D^i = k_1^{(i)} k_2^{(i)} k_3^{(i)} \ldots. k_{N-1}^{(i)} k_N^{(i)} k_B^{(i)} x_B^i$$

$$x_D^j = k_1^{(j)} k_2^{(j)} k_3^{(j} \ldots. k_{N-1}^{(j)} k_N^{(j)} k_B^{(j)} x_B^j$$

Dividing with each other

$$\frac{x_D^i}{x_D^j} = \frac{k_1^{(i)} k_2^{(i)} k_3^{(i)} \ldots. k_{N-1}^{(i)} k_N^{(i)} k_B^{(i)} x_B^i}{k_1^{(j)} k_2^{(j)} k_3^{(j} \ldots. k_{N-1}^{(j)} k_N^{(j)} k_B^{(j)} x_B^j}$$

$$\frac{k_1^i}{k_1^j} = \alpha_1^{ij}$$

$$\Rightarrow \frac{x_D^i}{x_D^j} = \alpha_1^{(ij)} \alpha_2^{(ij)} \alpha_3^{(ij)} \ldots \alpha_{N-1}^{(ij)} \alpha_N^{(ij)} \alpha_B^{(ij)} \frac{x_B^i}{x_B^j}$$

$$\alpha_1^{(ij)} \alpha_2^{(ij)} \alpha_3^{(ij)} \ldots \alpha_{N-1}^{(ij)} \alpha_N^{(ij)} \alpha_B^{(ij)} = (\alpha_{average}^{(ij)})^N$$

Similar to the concept of geometric mean

$$\Rightarrow \frac{x_D^i}{x_D^j} = (\alpha_{average}^{(ij)})^N \frac{x_B^i}{x_B^j}$$

$$\Rightarrow (\alpha_{average}^{(ij)})^N = \frac{x_D^i / x_D^j}{x_B^i / x_B^j}$$

$$\Rightarrow N = N_{min} = \frac{ln\left(\frac{x_D^i / x_D^j}{x_B^i / x_B^j}\right)}{ln\left(\alpha_{average}^{(ij)}\right)}$$

Fenske Equation

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Minimum number of stages: N_{min}

Fenske Equation

$$N = N_{min} = \frac{ln\left(\frac{x_D^i / x_D^j}{x_B^i / x_B^j}\right)}{ln\left(\alpha_{average}^{(ij)}\right)}$$

We can write in terms of fractional recovery which is usually specified $FR_D^{(LK)}$ and $FR_B^{(HK)}$

$$\frac{FR_D^{(i)}}{1 - FR_D^{(i)}} = \frac{Dx_D^{(i)}}{Bx_B^{(i)}}$$

$$N_{min} = \frac{\ln\left[\left(\frac{FR_D^{(1)}}{1 - FR_D^{(1)}}\right)\left(\frac{FR_B^{(2)}}{1 - FR_B^{(2)}}\right)\right]}{\ln\left(\alpha_{average}^{(12)}\right)}$$

Usually, component 1 is LK, and component 2 is HK

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Explanation

$$N_{\min} = \frac{\ln\left(\frac{x_D^{(1)}}{x_D^{(2)}}\frac{x_B^{(2)}}{x_B^{(1)}}\right)}{\ln\left(\alpha_{average}^{(12)}\right)}$$

Usually, component 1 is LK, and component 2 is HK

$$FR_D^{(1)} = \frac{Dx_D^{(1)}}{Fz^{(1)}} \qquad FR_B^{(1)} = \frac{Bx_B^{(1)}}{Fz^{(1)}}$$

$$N_{\min} = \frac{\ln\left(\frac{Dx_D^{(1)}}{Dx_D^{(2)}}\frac{Bx_B^{(2)}}{Bx_B^{(1)}}\right)}{\ln\left(\alpha_{average}^{(12)}\right)}$$

$$\frac{Dx_D^{(1)}}{Bx_B^{(1)}} = \frac{FR_D^{(1)}}{FR_B^{(1)}} = \frac{FR_D^{(1)}}{1-FR_D^{(1)}}$$

$$\frac{Bx_B^{(2)}}{Dx_D^{(2)}} = \frac{FR_B^{(2)}}{FR_D^{(2)}} = \frac{FR_B^{(2)}}{1-FR_B^{(2)}}$$

$$N_{\min} = \frac{\ln\left(\frac{Dx_D^{(1)}}{Bx_B^{(1)}}\frac{Bx_B^{(2)}}{Dx_D^{(2)}}\right)}{\ln\left(\alpha_{average}^{(12)}\right)}$$

$$N_{\min} = \frac{\ln\left[\left(\frac{FR_D^{(1)}}{1-FR_D^{(1)}}\right)\left(\frac{FR_B^{(2)}}{1-FR_B^{(2)}}\right)\right]}{\ln\left(\alpha_{average}^{(12)}\right)}$$

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Fractional recovery of non-keys: Fenske Equation

$$N_{\min} = \frac{\ln\left[\left(\frac{FR_D^{(1)}}{1-FR_D^{(1)}}\right)\left(\frac{FR_B^{(2)}}{1-FR_B^{(2)}}\right)\right]}{\ln\left(\alpha_{average}^{(12)}\right)}$$

$$\left(\frac{FR_D^{(1)}}{1-FR_D^{(1)}}\right)\left(\frac{FR_B^{(2)}}{1-FR_B^{(2)}}\right) = \left(\alpha_{average}^{(12)}\right)^{N_{\min}}$$

$$FR_D^{(1)} = \frac{\left(\alpha_{average}^{(12)}\right)^{N_{\min}}}{\left(\alpha_{average}^{(12)}\right)^{N_{\min}} + \left(\frac{FR_B^{(2)}}{1-FR_B^{(2)}}\right)}$$

The equation can be adapted for non-keys

$$FR_D^{(3)} = \frac{\left(\alpha_{average}^{(32)}\right)^{N_{\min}}}{\left(\alpha_{average}^{(32)}\right)^{N_{\min}} + \left(\frac{FR_B^{(2)}}{1-FR_B^{(2)}}\right)}$$

$$FR_B^{(4)} = \frac{\left(\alpha_{average}^{(41)}\right)^{N_{\min}}}{\left(\alpha_{average}^{(41)}\right)^{N_{\min}} + \left(\frac{FR_D^{(1)}}{1-FR_D^{(1)}}\right)}$$

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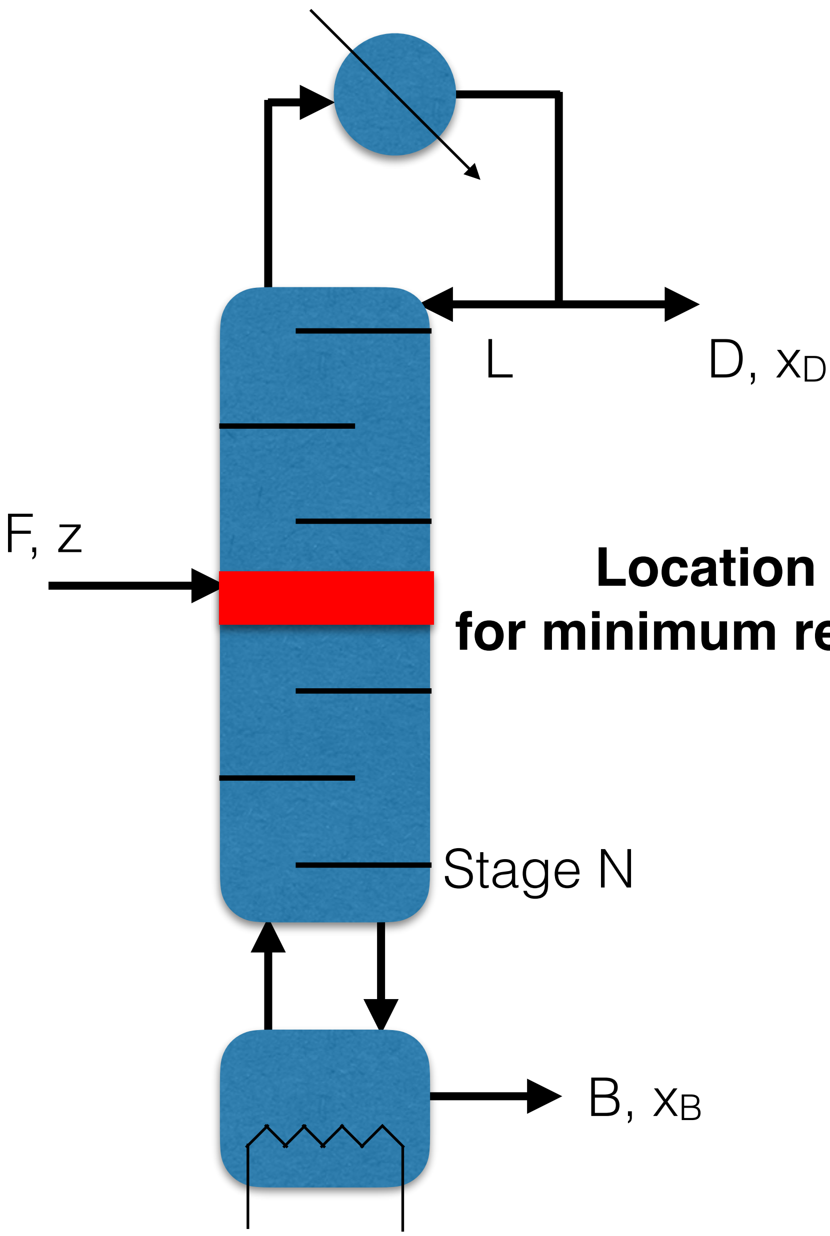
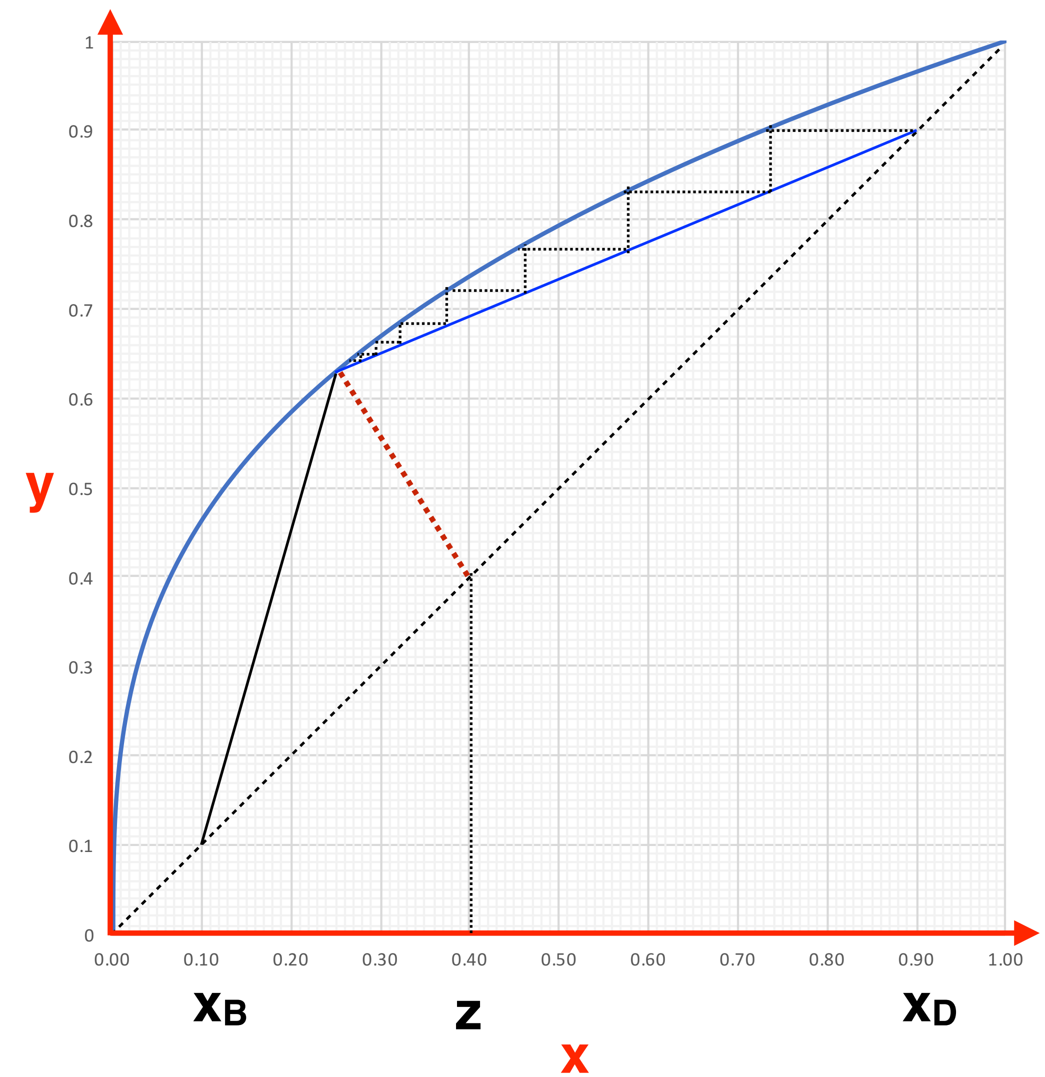
Recap: minimum reflux ratio in binary distillation



Location of pinch point for minimum reflux is at feed plate



At pinch point, operating and equilibrium line meet

An analytical equation can be derived in absence of graphical method

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Analytical method for minimum reflux ratio in binary distillation

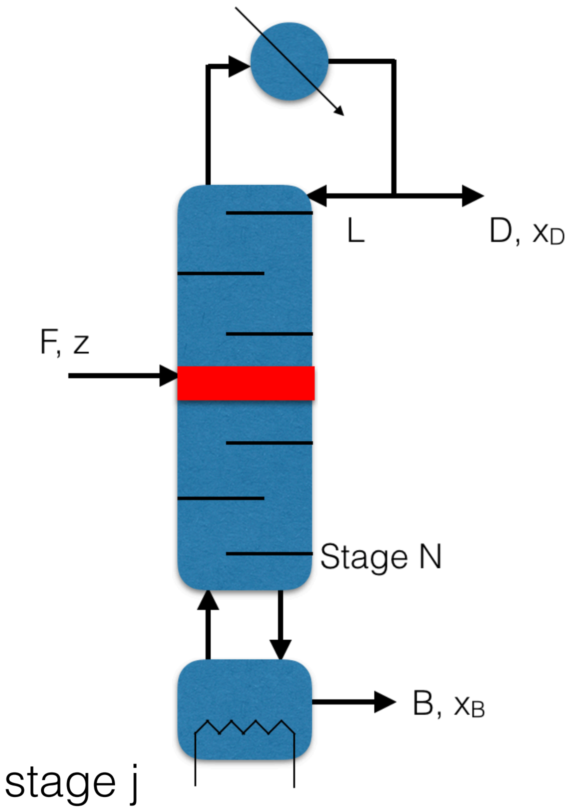
At pinch point compositions do not change from stage to stage

$$x_{j-1}^{(1)} = x_j^{(1)} = x_{j+1}^{(1)}$$

$$y_{j-1}^{(1)} = y_j^{(1)} = y_{j+1}^{(1)}$$

Equilibrium

$$y_j^{(1)} = k_j^{(1)} x_j^{(1)}$$



Operating equation in the rectifying section near pinch point

$$V_{min} y_{j+1}^{(1)} = L_{min} x_j^{(1)} + D x_D^{(1)}$$

$$\Rightarrow V_{min} y_j^{(1)} = L_{min} x_j^{(1)} + D x_D^{(1)}$$

Compositions do not change near stage j

$$\Rightarrow V_{min} y_j^{(1)} = L_{min} \frac{y_j^{(1)}}{k_j^{(1)}} + D x_D^{(1)}$$

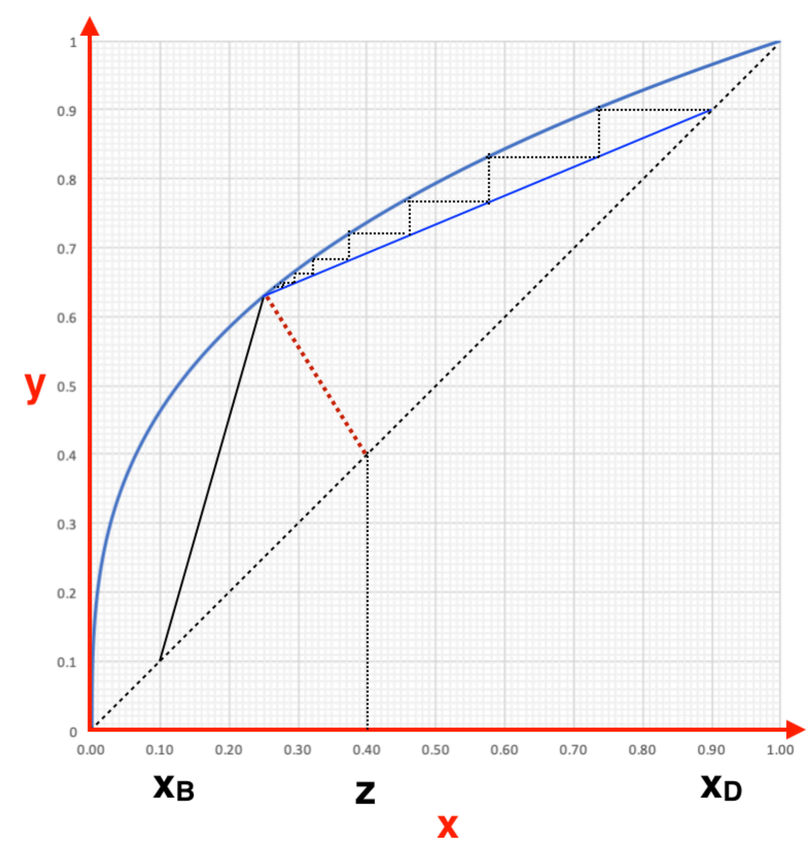
Equilibrium

$$\Rightarrow V_{min} y_j^{(1)} \left(1 - \frac{L_{min}}{k_j^{(1)} V_{min}}\right) = D x_D^{(1)}$$

$$\Rightarrow V_{min} y_j^{(1)} = \frac{D x_D^{(1)}}{\left(1 - \frac{L_{min}}{k_j^{(1)} V_{min}}\right)}$$

$$\Rightarrow \Sigma V_{min} y_j^{(i)} = V_{min} = \sum \frac{D x_D^{(i)}}{\left(1 - \frac{L_{min}}{k_j^{(i)} V_{min}}\right)}$$

Summation for component 1 and 2; i =1 and 2



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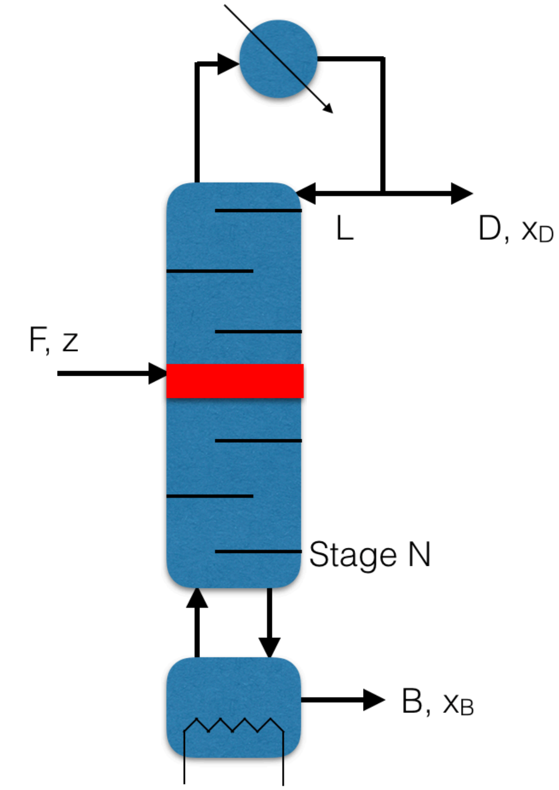
Analytical method for minimum reflux ratio in binary distillation



Operating equation in the stripping section near pinch point

$$\bar{V}_{min} y_{l+1}^{(1)} = \bar{L}_{min} x_l^{(1)} - B x_B^{(1)}$$

$$\Rightarrow \bar{V}_{min} y_l^{(1)} = \bar{L}_{min} x_l^{(1)} - B x_B^{(1)}$$

Compositions do not change

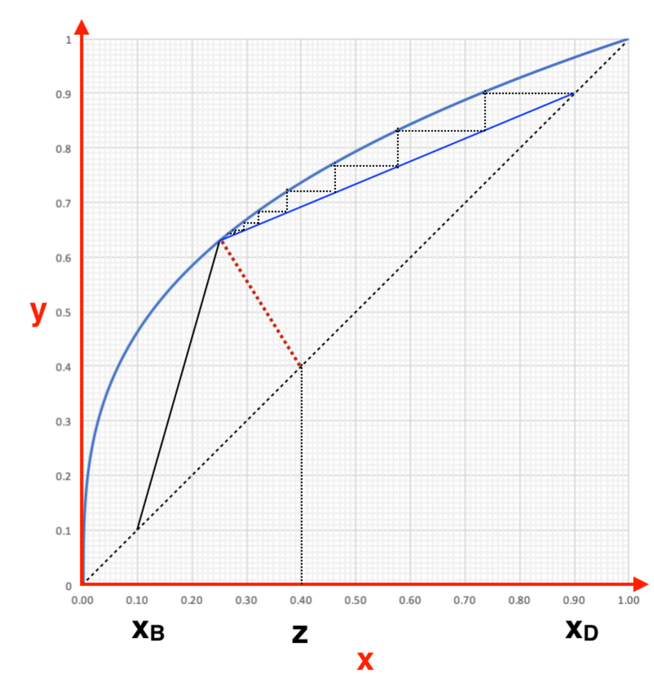
$$\Rightarrow \bar{V}_{min} y_l^{(1)} = \bar{L}_{min} \frac{y_l^{(1)}}{k_l^{(1)}} - B x_B^{(1)}$$

Equilibrium

$$\Rightarrow \bar{V}_{min} = -\sum \frac{B x_B^{(i)}}{\left(1 - \frac{\bar{L}_{min}}{k_l^{(i)} \bar{V}_{min}}\right)} \qquad V_{min} = \sum \frac{D x_D^{(i)}}{\left(1 - \frac{L_{min}}{k_j^{(i)} V_{min}}\right)}$$

Subtracting

$$V_{min} - \bar{V}_{min} = F(1-q) = \sum \frac{D x_D^{(i)}}{\left(1 - \frac{L_{min}}{k_j^{(i)} V_{min}}\right)} + \sum \frac{B x_B^{(i)}}{\left(1 - \frac{\bar{L}_{min}}{k_l^{(i)} \bar{V}_{min}}\right)}$$



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Analytical method for minimum reflux ratio in multicomponent distillation

$$F(1-q) = \sum \frac{Dx_D^{(i)}}{\left(1 - \frac{L_{min}}{k_j^{(i)} V_{min}}\right)} + \sum \frac{Bx_B^{(i)}}{\left(1 - \frac{\bar{L}_{min}}{k_l^{(i)} \bar{V}_{min}}\right)}$$

$$\alpha_j^{(i,HK)} = \frac{k_j^{(i)}}{k_j^{(HK)}} \qquad \alpha_l^{(i,HK)} = \frac{k_l^{(i)}}{k_l^{(HK)}}$$

$$\Rightarrow F(1-q) = \sum \frac{Dx_D^{(i)}}{\left(1 - \frac{L_{min}}{\alpha_j^{(i,HK)} k_j^{(HK)} V_{min}}\right)} + \sum \frac{Bx_B^{(i)}}{\left(1 - \frac{\bar{L}_{min}}{\alpha_l^{(i,HK)} k_l^{(HK)} \bar{V}_{min}}\right)}$$

constant relative volatility

$$\alpha_j^{(i,HK)} = \alpha_l^{(i,HK)} = \alpha^{(i,HK)}$$

$$\Rightarrow F(1-q) = \sum \frac{\alpha^{(i,HK)} Dx_D^{(i)}}{\left(\alpha^{(i,HK)} - \frac{L_{min}}{k_j^{(HK)} V_{min}}\right)} + \sum \frac{\alpha^{(i,HK)} Bx_B^{(i)}}{\left(\alpha^{(i,HK)} - \frac{\bar{L}_{min}}{k_l^{(HK)} \bar{V}_{min}}\right)}$$

Underwood showed that $\frac{L_{min}}{k_j^{(HK)} V_{min}} = \frac{\bar{L}_{min}}{k_l^{(HK)} \bar{V}_{min}} = \phi$

$$\Rightarrow F(1-q) = \sum \frac{\alpha^{(i,HK)} Dx_D^{(i)}}{\left(\alpha^{(i,HK)} - \phi\right)} + \sum \frac{\alpha^{(i,HK)} Bx_B^{(i)}}{\left(\alpha^{(i,HK)} - \phi\right)} = \sum \frac{\alpha^{(i,HK)}\left(Dx_D^{(i)} + Bx_B^{(i)}\right)}{\left(\alpha^{(i,HK)} - \phi\right)} = \sum \frac{\alpha^{(i,HK)}\left(Fz_i\right)}{\left(\alpha^{(i,HK)} - \phi\right)}$$

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Analytical method for minimum reflux ratio in multicomponent distillation

$$F(1-q) = \sum_{i=1}^{r} \frac{\alpha^{(i,HK)}\left(Fz_i\right)}{\left(\alpha^{(i,HK)} - \phi\right)} \qquad \Rightarrow (1-q) = \sum_{i=1}^{r} \frac{\alpha^{(i,HK)} z_i}{\left(\alpha^{(i,HK)} - \phi\right)}$$

r solution, pick a solution such that $\alpha^{(1,\mathrm{HK})} < \phi < \alpha^{(\mathrm{r,HK})}$

Understood showed that this is valid only for components which distribute (in distillate as well as bottom)

$$V_{min} = \sum \frac{Dx_D^{(i)}}{\left(1 - \frac{L_{min}}{k_j^{(i)} V_{min}}\right)} \qquad \alpha_{\mathrm{j}}^{(\mathrm{i,HK})} = \frac{\mathrm{k_j^{(i)}}}{\mathrm{k_j^{(HK)}}}$$

$$\Rightarrow V_{min} = \sum \frac{\alpha^{(i,HK)} Dx_D^{(i)}}{\left(\alpha^{(i,HK)} - \frac{L_{min}}{k_j^{(HK)} V_{min}}\right)} \qquad \phi = \frac{L_{min}}{k_j^{(HK)} V_{min}} = \frac{\bar{L}_{min}}{k_l^{(HK)} \bar{V}_{min}}$$

$$\Rightarrow V_{min} = \sum \frac{\alpha^{(i,HK)} Dx_D^{(i)}}{\left(\alpha^{(i,HK)} - \phi\right)}$$

$$V_{min} = L_{min} + D \qquad \Rightarrow L_{min} = V_{min} - D \qquad \Rightarrow R_{min} = \frac{L_{min}}{D}$$

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Calculation of Minimum Reflux in Distillation Columns

Three methods for calculating minimum reflux rates in distillation columns fractionating multicomponent mixtures are presented and evaluated. The first method is based on some overlooked

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volatility rates are valid. It is also suitable as an approximate method for all column design problems which normally occur. The third method is an adaptation of the Thiele and Geddes plate-

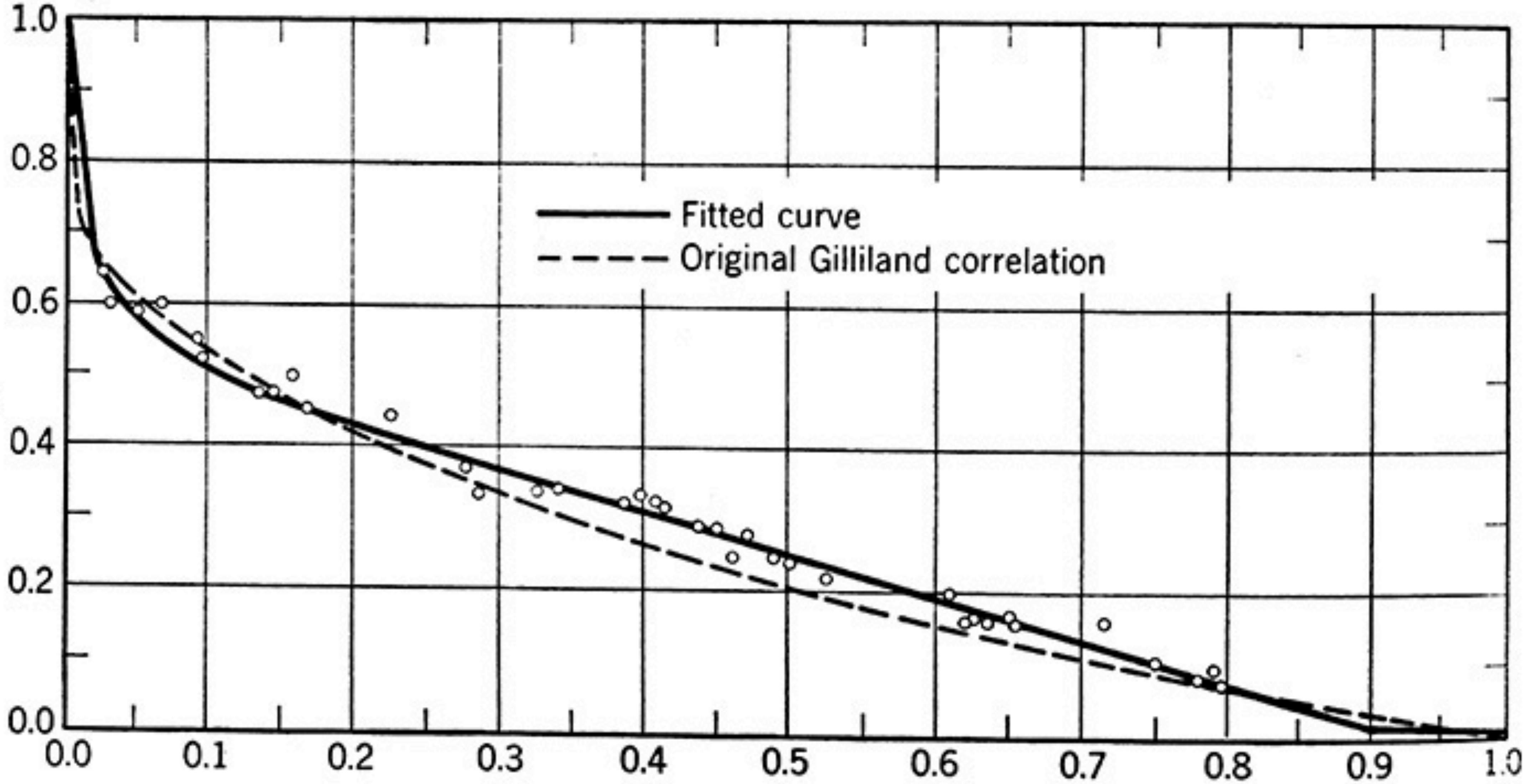
TABLE III. COMPUTATION OF MINIMUM REFLUX

$\Phi_{E,F} = 1.2477$

Compn.	α_{ir}	Recovery in Top Product, %	Comment	$d(X_i)_d$	Eq. 18 $\frac{1.2477\, d(X_i)_d}{\alpha_{ir} - 1.2477}$
A	10	100	Nondistributing	0.050	0.0071
B	5	100	Nondistributing	0.050	0.0166
C	2.05	94	From Table II	0.094	0.1462
D	2.0	90	Light key	0.270	0.4478
E	1.5	50	From Table II	0.025	0.1237
F	1.0	10	Heavy key	0.030	−0.1511
G	0.9	2	From Table II	0.002	−0.0072
H	0.1	0	Nondistributing	...	....
				$d = 0.512$	$0.5831 = L_{min}$

Approximate method for multicomponent: Gilliland correlation for number of stages

You can use fitted curve



$$\frac{N - N_{\min}}{N+1}$$

$$\frac{R - R_{\min}}{R+1}$$

Optimum feed plate

Empirical equation of Kirkbridge (1944)

$$\frac{N_{rectifying\_section}}{N_{stripping\_section}} = \left[\left(\frac{z^{(HK)}}{z^{(LK)}} \right) \left(\frac{x_B^{(LK)}}{x_D^{(HK)}} \right)^2 \left(\frac{B}{D} \right) \right]^{0.206}$$

Approximate method to calculate number of stages

Fenske-Underwood-Gilliland method

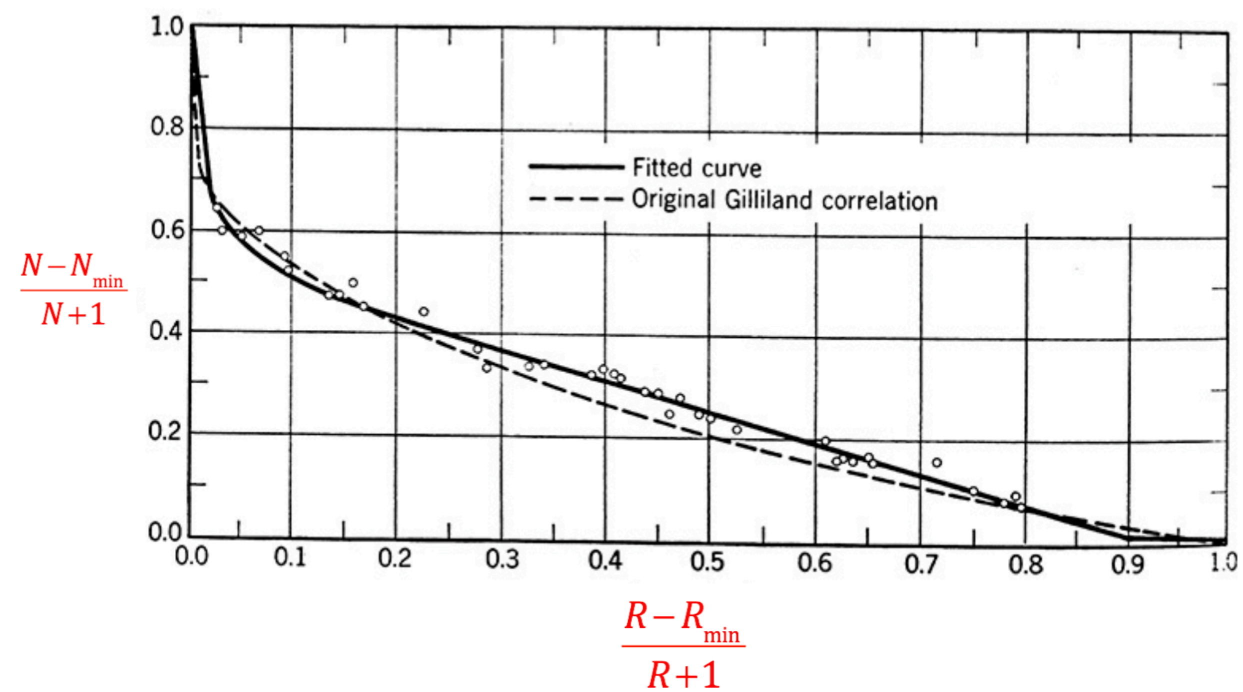
Approximation of the minimum number of stages, N_{min}

↓

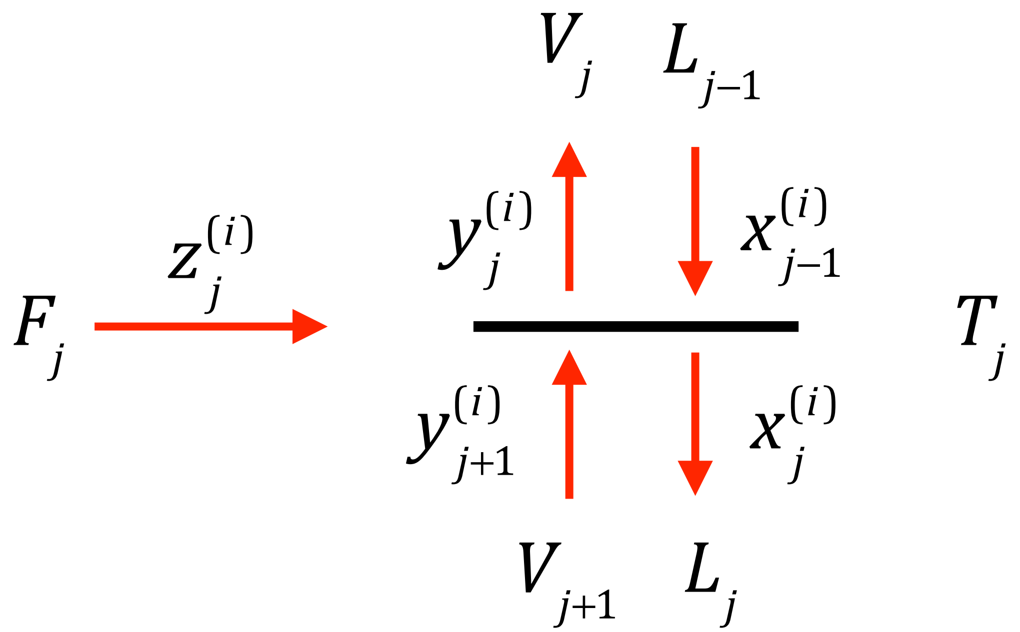
Approximation of the minimum reflux ratio, R_{min}

↓

Approximation of number of stages for $R > R_{min}$



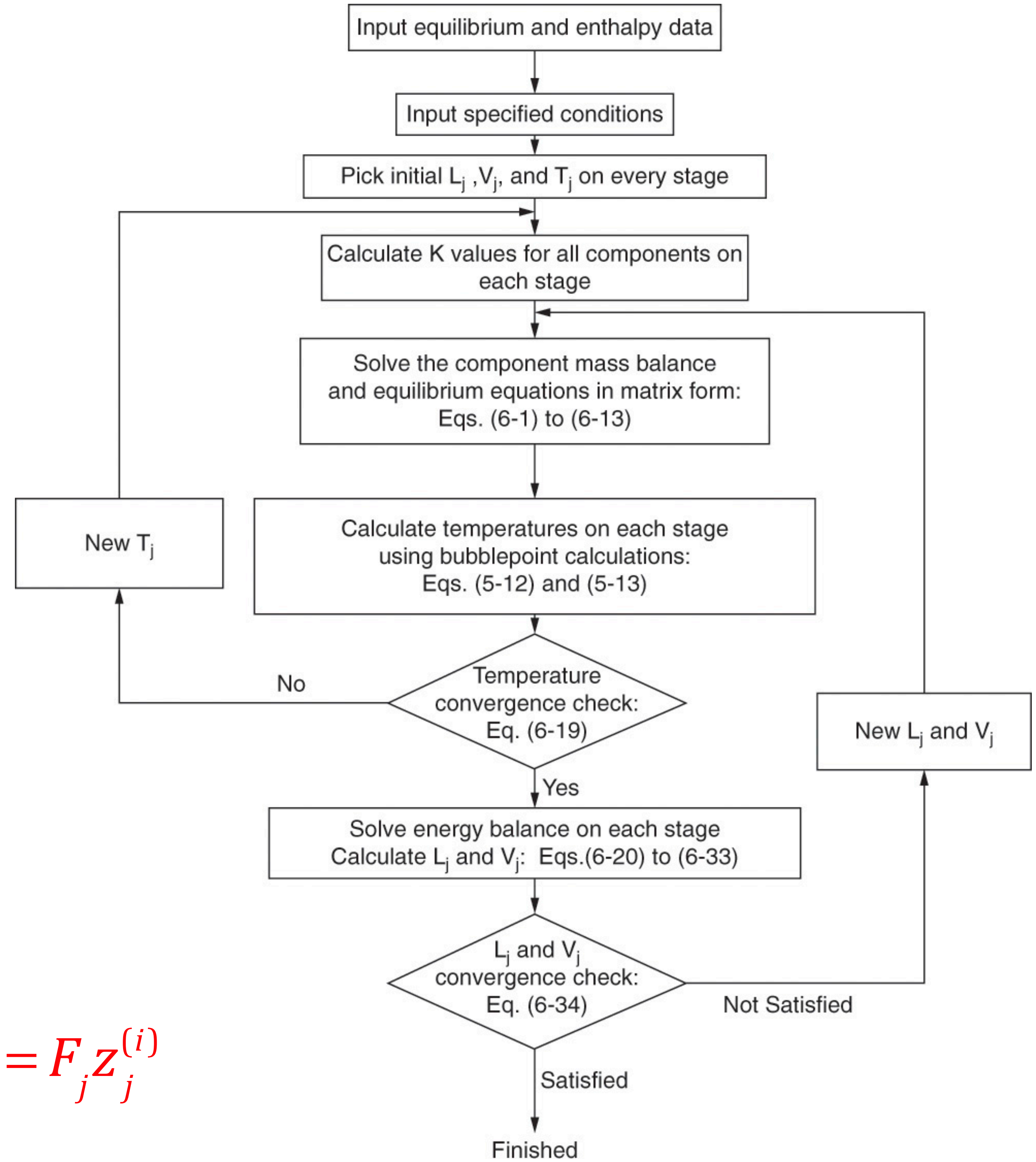
Exact calculation for multicomponent distillation



$$V_j y_j^{(i)} + L_j x_j^{(i)} - V_{j+1} y_{j+1}^{(i)} - L_{j-1} x_{j-1}^{(i)} = F_j z_j^{(i)}$$

$$y_j^{(i)} = K_j^{(i)} x_j^{(i)}$$

$$V_j K_j^{(i)} x_j^{(i)} + L_j x_j^{(i)} - V_{j+1} K_{j+1}^{i} x_{j+1}^{(i)} - L_{j-1} x_{j-1}^{(i)} = F_j z_j^{(i)}$$



Exercise Problem 1

A three component feed (100 mole/hr, saturated liquid, LNK 10%, LK 55%, HK 35%) is to be separated in a distillation column. Desired recovery for LK in distillate is 99.5%. Assume constant relative volatility. LNK does not go to bottom.

$x_D^{(LK)} = 0.75$ $\alpha^{(LNK,LK)} = 4$ $\alpha^{(HK,LK)} = 0.75$

1. Calculate B, D, and $\alpha_{LK,HK}$, $\alpha_{LNK,HK}$, $\alpha_{HK,HK}$.
2. Calculate minimum number of stages by the Fenske method.
3. Using Underwood equation, calculate possible values of ϕ
4. If R = 1.2 R_{min}, calculate the number of stages by Gilliland method.

$$N_{\min} = \frac{\ln\left[\left(\frac{FR_D^{(1)}}{1-FR_D^{(1)}}\right)\left(\frac{FR_B^{(2)}}{1-FR_B^{(2)}}\right)\right]}{\ln\left(\alpha_{average}^{(12)}\right)}$$

$$(1-q) = \sum_{i=1}^{r} \frac{\alpha^{(i,HK)} z_i}{\left(\alpha^{(i,HK)} - \phi\right)}$$

$$0.995 = \frac{D * 0.75}{100 * 0.55} \quad \Rightarrow D = 99.5 * 55/75 = 73 \text{ mole/hr} \quad \Rightarrow B = 100 - 73 = 27 \text{ mole/hr}$$

$$0.005 = \frac{27 * x_B^{(LK)}}{100 * 0.55} \quad \Rightarrow x_B^{(LK)} = 0.01 \quad \Rightarrow x_B^{(HK)} = 0.99 \quad \Rightarrow FR_B^{(HK)} = \frac{0.99 * 27}{100 * 0.35} = 76.4\,\%$$

LNK does not go to bottom

$$\alpha^{(LK,HK)} = 1/\alpha^{(HK,LK)} = 1.33$$

$$N_{min} = \ln(0.995/0.005 * 0.764/0.236)/\ln(1.33) = 22.7$$

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A three component feed (100 mole/hr, saturated liquid, LNK 10%, LK 55%, HK 35%) is to be separated in a distillation column. Desired recovery for LK in distillate is 99.5%. Assume constant relative volatility.

$$x_D^{(LK)} = 0.75 \qquad \alpha^{(LNK,LK)} = 4 \qquad \alpha^{(HK,LK)} = 0.75$$

$$\alpha^{(LNK,HK)} = k_{LNK}/k_{HK} = k_{LNK}/k_{LK} * k_{LK}/k_{HK} = \alpha^{(LNK,LK)} * \alpha^{(LK,HK)} = 4 * 1.33 = 5.32 \qquad \alpha_{HK,HK} = 1$$

$$(1-q) = \sum_{i=1}^{r} \frac{\alpha^{(i,HK)} z_i}{\left(\alpha^{(i,HK)} - \phi\right)} \qquad \Rightarrow 0 = \frac{5.32*(0.1)}{5.32-\phi} + \frac{1.33*(0.55)}{1.33-\phi} + \frac{1*(0.35)}{1-\phi}$$

$$q = 1$$

$$\Rightarrow 0 = \frac{0.53}{5.32-\phi} + \frac{0.73}{1.33-\phi} + \frac{0.35}{1-\phi}$$

$$\Rightarrow 0.53(1.33-\phi)*(1-\phi) + 0.73(5.32-\phi)(1-\phi) + 0.35(5.32-\phi)(1.33-\phi) = 0$$

$$\phi = 1.10 \; or \; 3.98 \qquad 1 < \phi < \alpha^{(r,HK)}$$

LNK does not distribute, so not considered

$$1 < \phi < 1.33$$

$$\Rightarrow \phi = 1.10$$

$$V_{min} = \sum \frac{\alpha^{(i,HK)} D x_D^{(i)}}{\left(\alpha^{(i,HK)} - \phi\right)}$$

We need to calculate x_D

EPFL

A three component feed (100 mole/hr, saturated liquid, LNK 10%, LK 55%, HK 35%) is to be separated in a distillation column. Desired recovery for LK in distillate is 99.5%. Assume constant relative volatility.

$\alpha^{(LK,HK)} = 1.33$ $\alpha^{(LNK,HK)} = 5.32$ $\alpha_{HK,HK} = 1$

$$0.236 = \frac{73 * x_D^{(HK)}}{100 * 0.35}$$ $x_D \; for \; HK = 0.11$

	LNK	LK	HK
alpha (i, HK)	5.32	1.33	1
xD	0.14	0.75	0.11

$\phi = 1.10$

$$V_{min} = \sum \frac{\alpha^{(i,HK)} D x_D^{(i)}}{\left(\alpha^{(i,HK)} - \phi\right)} = 249$$

$V_{min} = L_{min} + D$ $\Rightarrow L_{min} = V_{min} - D = 176$

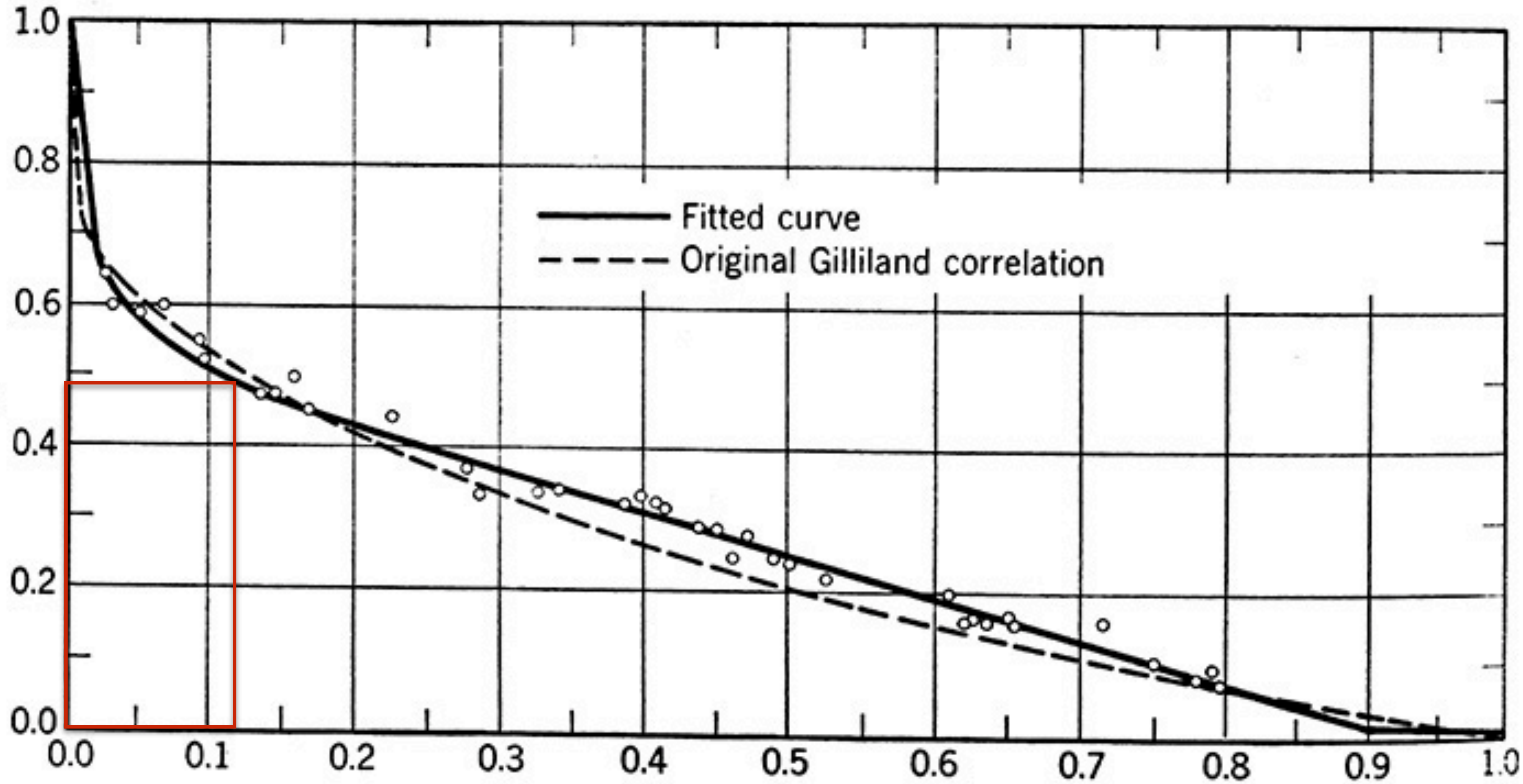
$$\frac{R - R_{min}}{R+1}$$

$\Rightarrow R_{min} = \frac{L_{min}}{D} = 2.4$ $\Rightarrow R = 1.2 R_{min} = 2.88$ $\Rightarrow \frac{R - R_{min}}{R+1} = \frac{0.48}{3.88} = 0.12$

EPFL

$$\Rightarrow \frac{R - R_{min}}{R+1} = 0.12 \qquad \Rightarrow \frac{N - N_{min}}{N+1} = 0.48 \qquad \Rightarrow \frac{N - 22.7}{N+1} = 0.48$$

$N = 44.6$ implying 45 stages



$$\frac{N - N_{\min}}{N+1}$$

$$\frac{R - R_{\min}}{R+1}$$

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