SKF4153- PLANT DESIGN

DISTILLATION SEQUENCE

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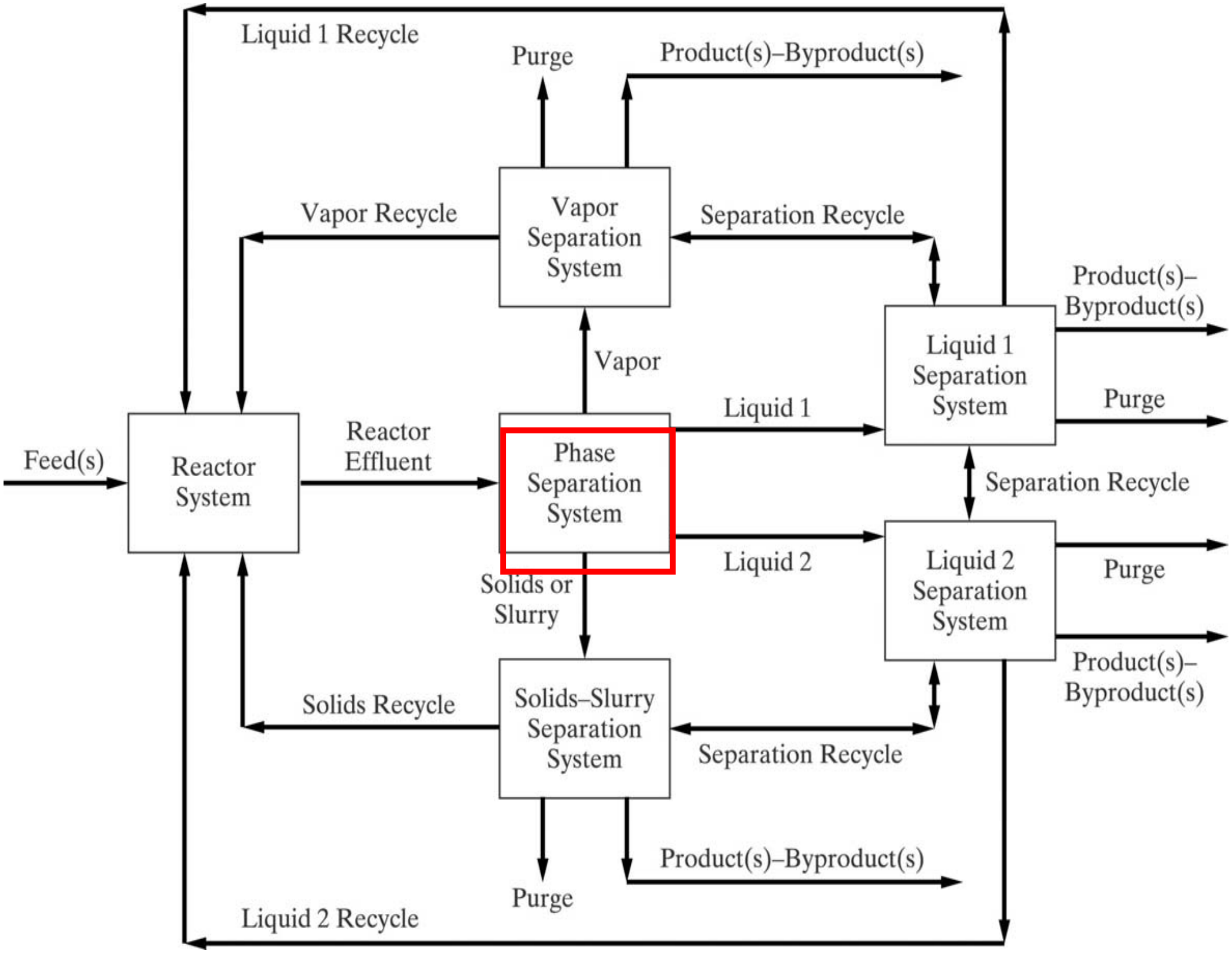
Separation Systems



Reference:J.M. Douglas, Conceptual Design of Chemical Processes, McGraw Hill, 1998.

SEPARATION FACTOR

- The separation factor, *SF*, defines the degree of separation achievable between two key components of the feed.

- SF is arranged (for calculation) to give value >1.0; possible separation. The larger the SF, the easier is to separate the mixtures.

- *SF* is generally limited by thermodynamic equilibrium.

$$SF = \frac{y_1/x_1}{y_2/x_2} = \frac{K_1}{K_2} = \alpha_{1,2}\left(= \frac{P_1^s}{P_2^s} \text{ for ideal VLE} \right)$$

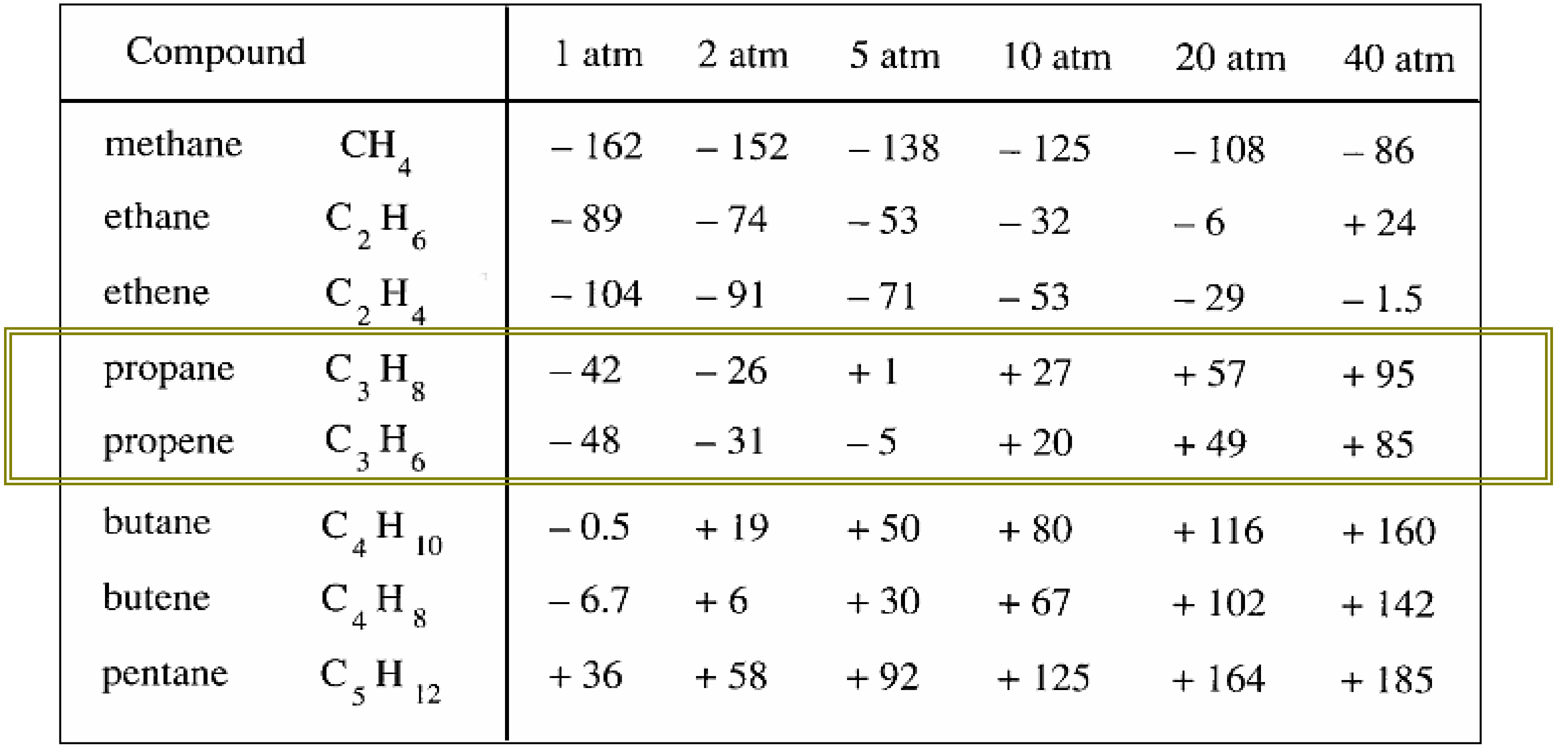
$\alpha_{1,2}$ = Relative Volatility

P_1^s = vapor pressure of species 1

Example

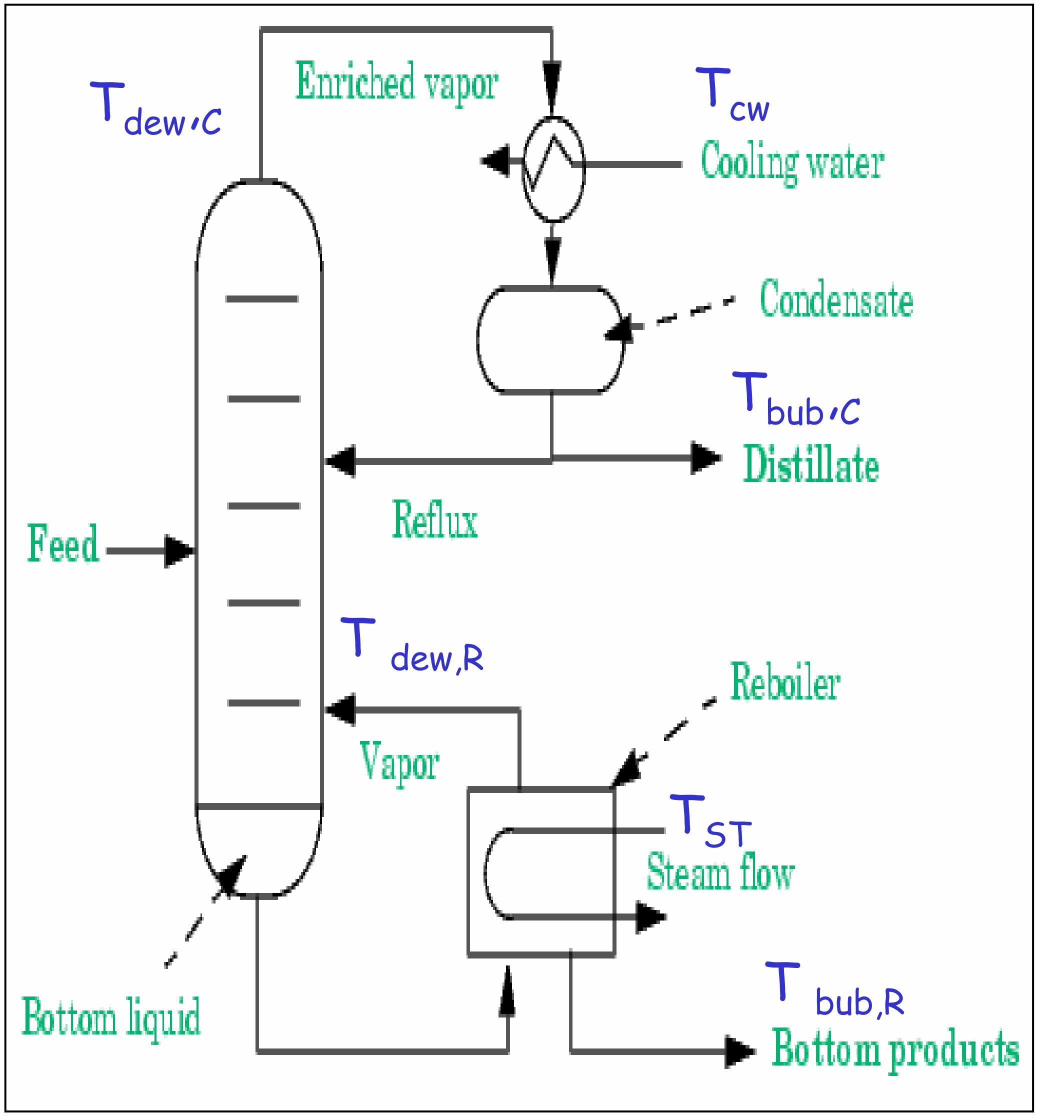
A liquid mixture containing 50 mole % propane (C3-), 50 mole % propene (C3=) is fed at a rate of 1000 mol/h to a distillation unit. Estimate the operating pressure for a column separating C3- from C3=, assuming cooling water at 30°C is available for use.

What would be the top temperature of the column?



Compound		1 atm	2 atm	5 atm	10 atm	20 atm	40 atm
methane	CH_4	– 162	– 152	– 138	– 125	– 108	– 86
ethane	C_2H_6	– 89	– 74	– 53	– 32	– 6	+ 24
ethene	C_2H_4	– 104	– 91	– 71	– 53	– 29	– 1.5
propane	C_3H_8	– 42	– 26	+ 1	+ 27	+ 57	+ 95
propene	C_3H_6	– 48	– 31	– 5	+ 20	+ 49	+ 85
butane	C_4H_{10}	– 0.5	+ 19	+ 50	+ 80	+ 116	+ 160
butene	C_4H_8	– 6.7	+ 6	+ 30	+ 67	+ 102	+ 142
pentane	C_5H_{12}	+ 36	+ 58	+ 92	+ 125	+ 164	+ 185

Column Temperature



RECALL

	T bp (K)	Tc (K)	A	B	C
n-butane	272.6	425	15.68	2154.9	-32.42
Benzene	353	562	15.9	2788.51	-52.34
Toulene	384	593	16.014	3096.52	-53.67

$\ln P^* = A - B/(T+C)$

(mmHg, K); 1 bar=750 mmHg

		Scenario 1		Scenario 2	
(kmol/h)	**FEED**	**D1**	**B1**	**D2**	**B2**
n-butane	20	20		20	
Benzene	30		30	30	
Toulene	50		50		50

- Explain bubble point and dew point?
- What are the bubble point and dew point of pure water?
- Calculate column pressure and T bub at the column bottoms for each scenario.
- Why cooling water can be used to condense n-butane (Boiling point=272.6K)?
- Calculate T dew for each scenario.
- Calculate relative volatility of the adjacent components if the feed entering at 310K.

Choose the right column pressure!!

Consider the separation of a mixture of 50 mol/hr of C_3H_8 (1) and 50 mol/hr C_3H_6 (2) at a pressure of 1.1 bar and a bubble point feed temperature of 230 K. Under these conditions, P^0_2=930.5 mm Hg and P^0_1=724.1 mm Hg and $\underline{\alpha_{1/2}=1.285}$. Setting the recoveries of the two components at 0.99 (lk,2) and 0.01 (hk,1), we find out that at total reflux, the minimum number of trays N_m (by Fenske Eqn) is

$$N_m = \ln\left[\frac{0.99}{0.01}.\frac{0.99}{0.01}\right] / \ln \alpha_{lk/hk} = 36.65$$

Now if the pressure is increased tenfold to P=10.94 bar, we have a bubble point feed temperature of 300 K and P^0_2=8975.6 mm Hg, and P^0_1=7458.5 mm and $\underline{\alpha_{1/2}=1.203}$. As a result, for the same recoveries, the separation becomes more difficult and the minimum number of trays increases to $\mathbf{N_m=49.72}$.

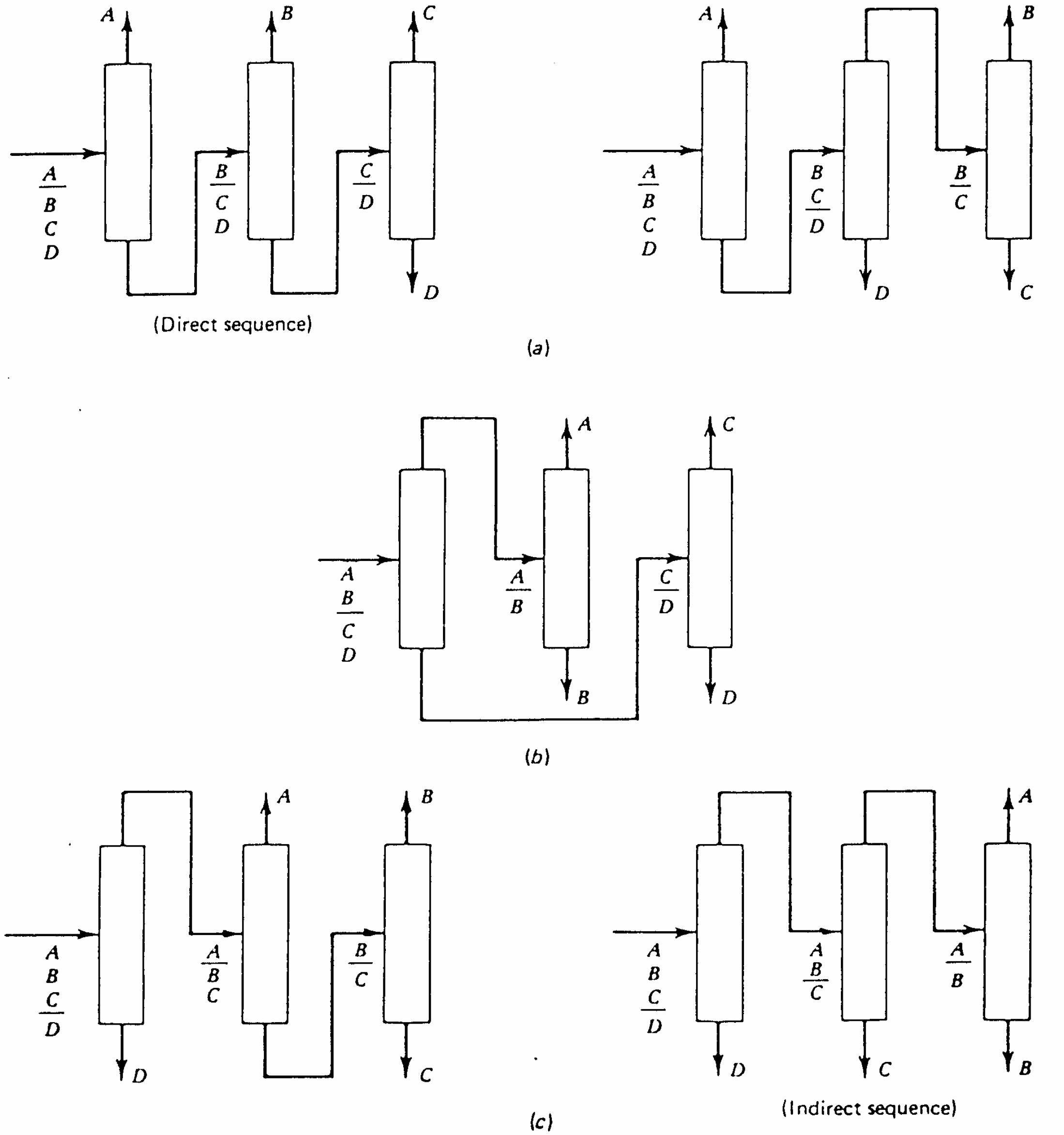
Sequences for Ordinary Distillation (OD)

Equation for number of different sequences of ordinary distillation (OD) columns, N_S, to produce P products:

$$N_s = \frac{[2(P-1)]!}{P!(P-1)!}$$

P	# of Separators	N_s
2	1	1
3	2	2
4	**3**	**5**
5	4	14

Sequences for <u>4-component separation</u>



__Reference__: W.D. Seider, J.D. Seider, D.R. Lewin, Product and Process Design Principles: Synthesis, Analysis and Evaluation, John Wiley and Sons, Inc., 2010.

Rule of thumb for distillation sequence

❶ Remove thermally unstable, corrosive, or chemically reactive components early in the sequence.

❷ Remove final products one-by-one as distillates (the direct sequence).

❸ Separate early in the sequence, those components of greatest molar percentage in the feed.

❹ Sequence separation points in the order of decreasing relative volatility so that the most difficult splits are made in the absence of other components.

❺ Sequence separation points to leave last those separations that give the highest purity products.

❻ Sequence separation points that favor near equimolar amounts of distillates and bottoms in each column. The reboiler duty is not excessive. (especially if energy cost high)

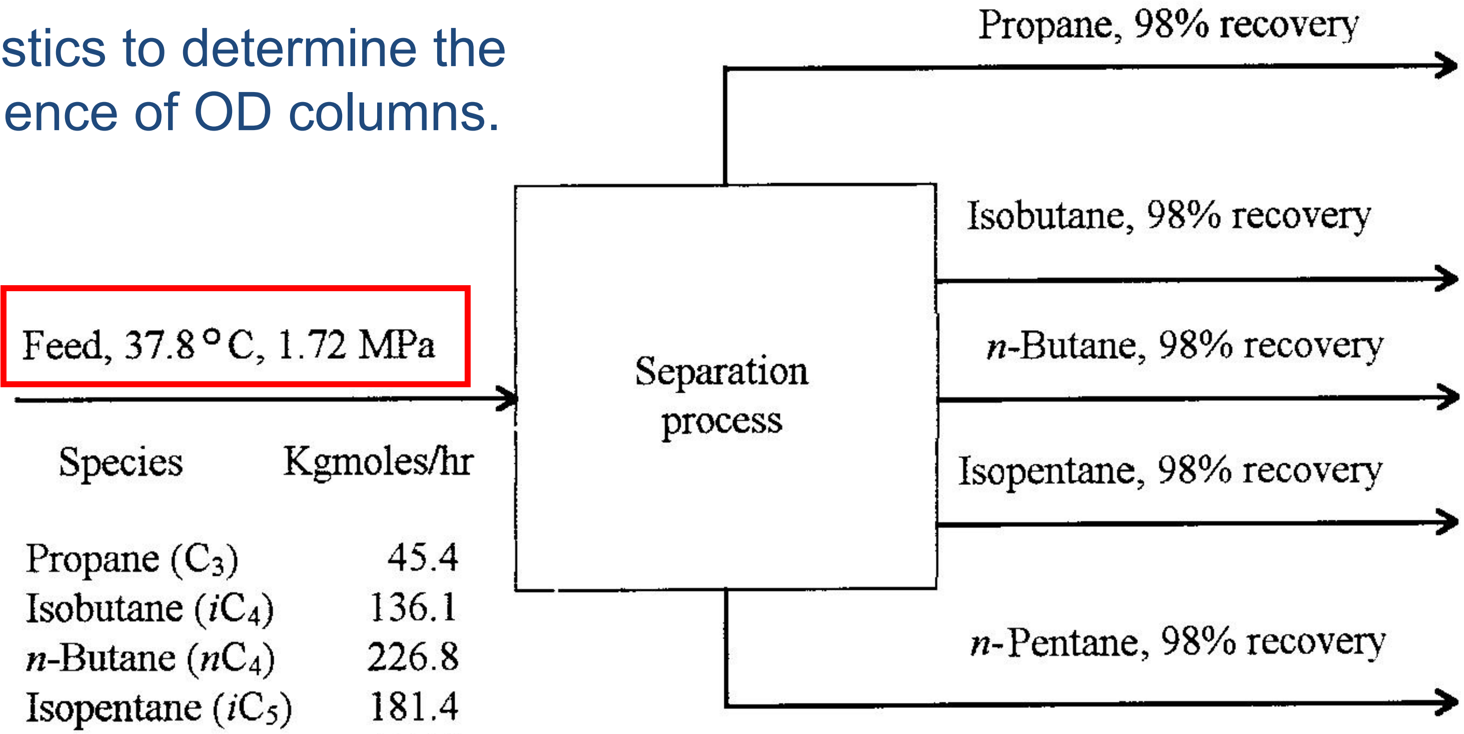
Reference: W.D. Seider, J.D. Seider, D.R. Lewin, Product and Process Design Principles: Synthesis, Analysis and Evaluation, John Wiley and Sons, Inc., 2010.

Arrange in the order of increasing boiling point

Component Pair	Approximate α at 1 atm
C_3/iC_4	3.6
iC_4/nC_4	1.5
nC_4/iC_5	2.8
iC_5/nC_5	1.35

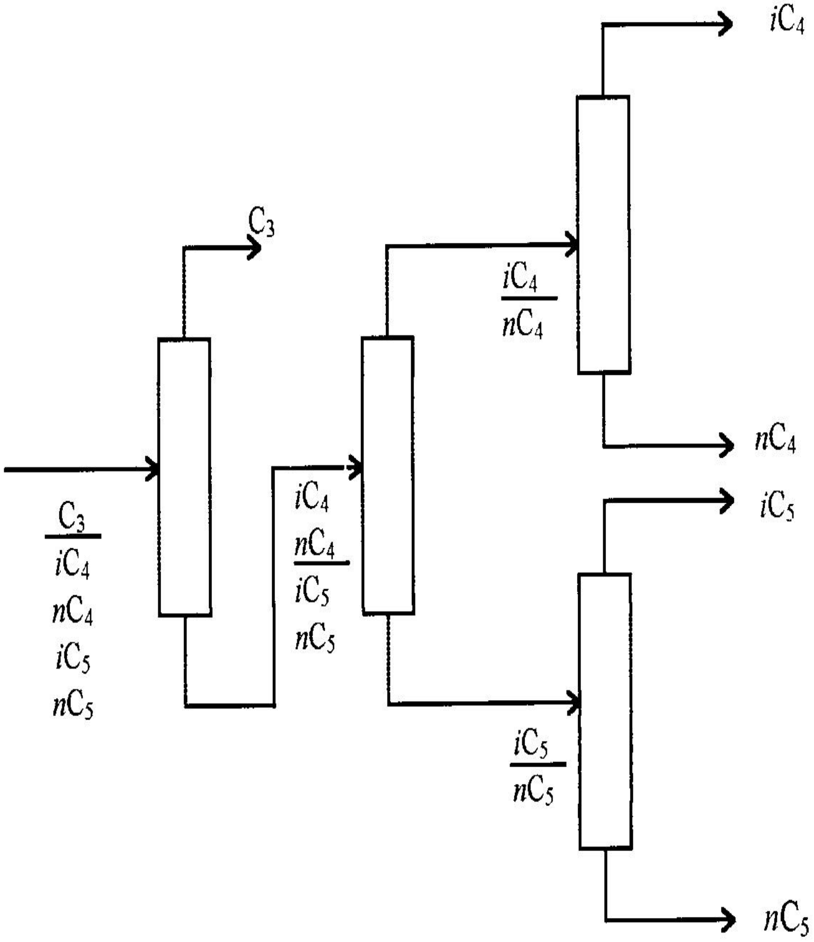
Question:

Use heuristics to determine the best sequence of OD columns.



Species	Kgmoles/hr
Propane (C_3)	45.4
Isobutane (iC_4)	136.1
n-Butane (nC_4)	226.8
Isopentane (iC_5)	181.4
n-Pentane (nC_5)	317.5
	907.2

- Variation in relative volatility and molar percentage.
- First column should separate C3 , the most volatile.
- Second column should be for separation of nC4 and iC5 as LK and HK respectively.
- Two most difficult splits are iC4/nC4 and iC5/nC5, so two separate columns for these separation



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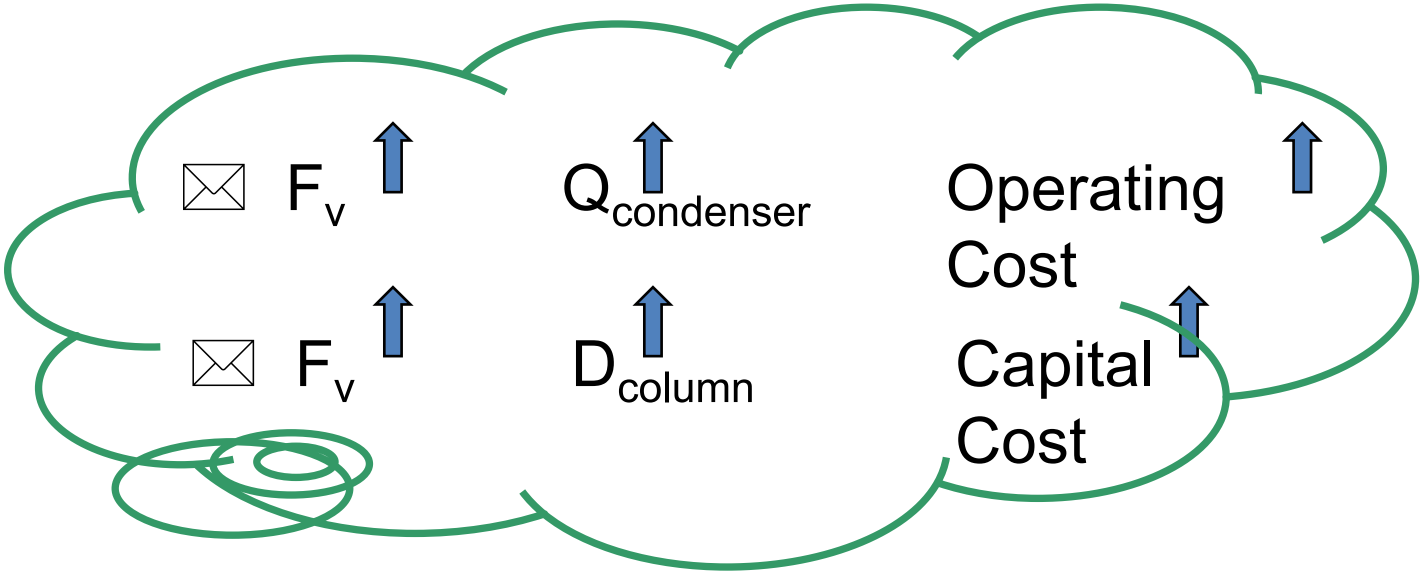
Vapour Flowrate Approach



☒ F_v ↑ $Q_{condenser}$ ↑ Operating Cost ↑

☒ F_v ↑ D_{column} ↑ Capital Cost ↑

Thus, favour sequence with the lowest vapour flowrate

Vapour flowrate estimation

$$V = D(1 + R)$$

Define $R_F = R/R_{min}$

$$\boxed{V = D(1 + R_F R_{min})} \quad \text{……} \textit{Equation 1}$$

(Use Underwood Equation to calculate R_{min})

Underwood Equation:

$$R_{min} = \frac{1}{\alpha - 1}\left[\frac{x_{DLK}}{x_{FLK}} - \alpha\cancel{\frac{x_{DHK}}{x_{FHK}}}\right]$$

~ 0 - Assuming sharp separation and LK and LLK o/head

$$R_{min} = \frac{1}{\alpha - 1}\left[\frac{F}{D}\right]$$

……Equation 2

Combine Equations (1) and (2), gives

$$V = D + \frac{R_F}{\alpha - 1} F$$

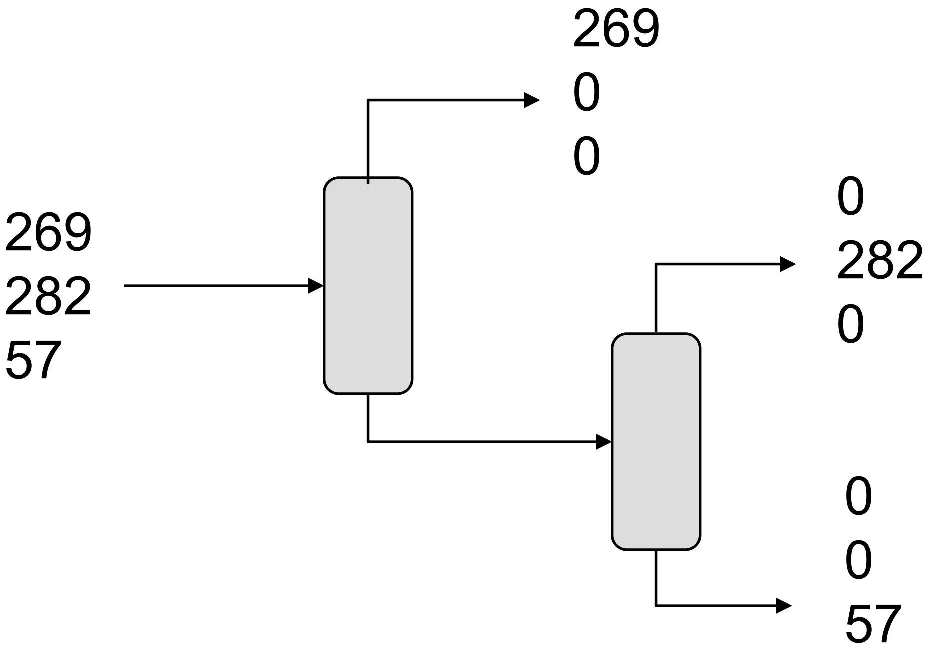
Example

The table below gives the data for a ternary separation of benzene, toluene and ethyl benzene. Using the vapour flowrate equation, determine whether direct or indirect sequence should be used.

Component	Flowrate (kmol/h)	Relative volatility	Relative volatility adjac. comp.
Benzene	269	3.53	1.96
Toluene	282	1.80	1.80
Ethyl Benzene	57	1.0	

$R_F = 1.1$

Solution:



269
282
57

269
0
0

0
282
0

0
0
57

For the direct sequence

First column

$$\sum V = 269 + (269 + 282 + 57)\,\frac{1.1}{(1.96 - 1)} + 282 + (282 + 57)\,\frac{1.1}{(1.8 - 1)}$$

Second column

$= 965.7 + 748.1$

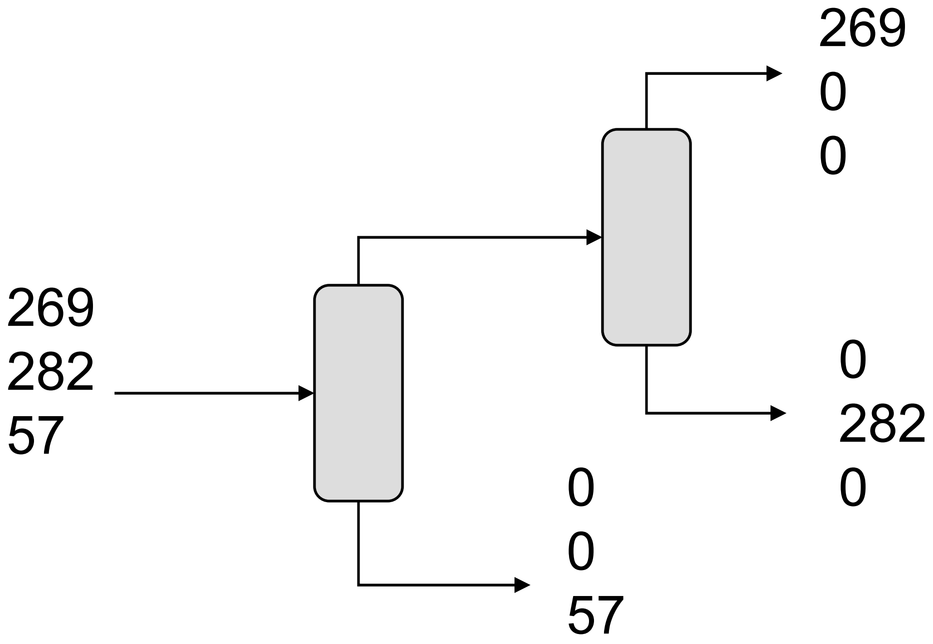
$= \mathbf{1713.8}$ kmol/h

For the indirect sequence

$$\sum V = (269 + 282) + (269 + 282 + 57)\frac{1.1}{(1.8 - 1)} + 269 + (269 + 282)\frac{1.1}{(1.96 - 1)}$$

$$= 1387 + 900.4$$

$$= 2287.4 \text{ kmol/h}$$



Hence, the direct sequence should be used. ***NOTE: High V, High Capital and Op. Costs!!***

ALSO TRY THIS ONE AT HOME

A stream is to be separated of Methane (bp –161ºC), benzene (bp 80ºC), toluene (bp 110ºC) and orthoxylene (bp 144ºC) of a composition of , respectively, 0.50, 0.10, 0.10, 0.30. What sequence of boiling-point exploitations will probably lead to the most economic separation?

(a) Use the heuristic approach
(b) Verify your answer in (a) using the vapour flowrate approach

Given:
Relative volatility 3.70, 2.5, 1.7 and 1.0
$R_F = 1.1$

References

- J.M. Coulson, J.F. Richardson, R.K. Sinnot, Chemical Engineering Vol. 6, Pergamon Press, 1985.
- J.M. Douglas, Conceptual Design of Chemical Processes, McGraw Hill, 1998.
- L.T. Biegler, I.E. Grossman, A.W. Westerberg, Systematic Methods of Chemical Process Design, Prentice Hall, 1997.
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