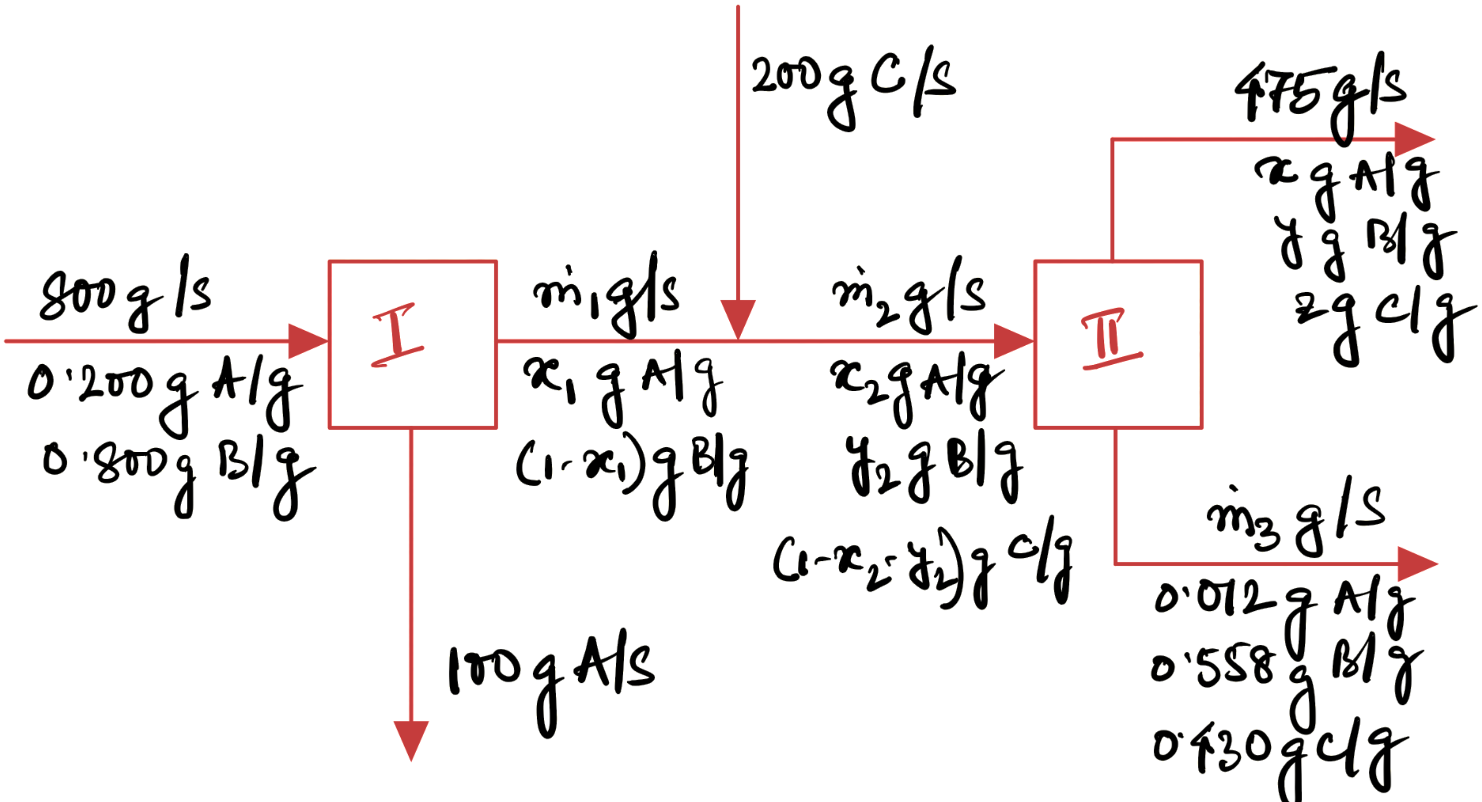
CHEMICAL PROCESS CALCULATIONS

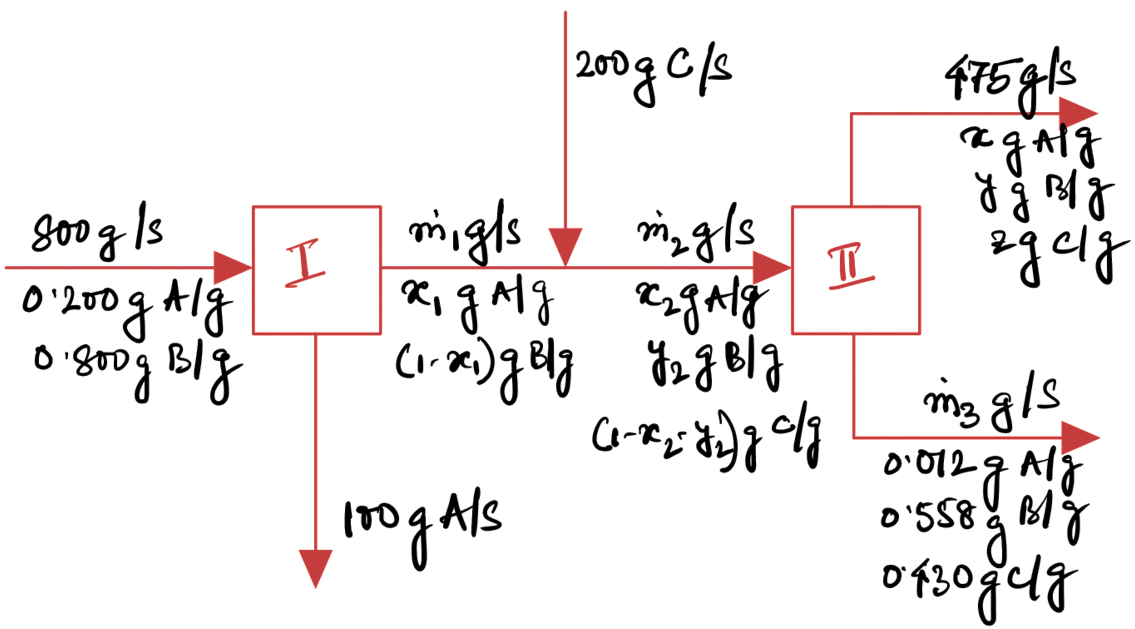
(Material Balance Calculations: Fundamentals & Single Unit)

Lecture # 7 & 8: September 06, 2022



⇒ Max. number of balance equations

⇒ Order of solution



Overall : 3
Unit I : 2
Unit II : 3
Mixing point : 3

Overall mass balance $\rightarrow \dot{m}_3$
Unit I - mass balance $\rightarrow \dot{m}_1$ & x_1
Mixing point - mass balance $\rightarrow \dot{m}_2$
" — A balance $\rightarrow x_2$
" — C " $\rightarrow y_2$

An equimolar liquid mixture of benzene and toluene is separated into two product streams inside a column, where a liquid stream flows downward and a vapor stream rises. At each point in the column some of the liquid vaporizes and some of the vapor condenses. The vapor leaving the top of the column, which contains 97 mole% benzene, is completely condensed and split into two equal fractions: one is taken off as the overhead product stream, and the other (the reflux) is recycled to the top of the column. The overhead product stream contains 89.2% of the benzene fed to the column. The liquid leaving the bottom of the column is fed to a partial reboiler in which 45% of it is vaporized. The vapor generated in the reboiler is recycled to become the rising vapor stream in the column, and the residual reboiler liquid is taken off as the bottom product stream. The compositions of the streams leaving the reboiler are governed by the relation

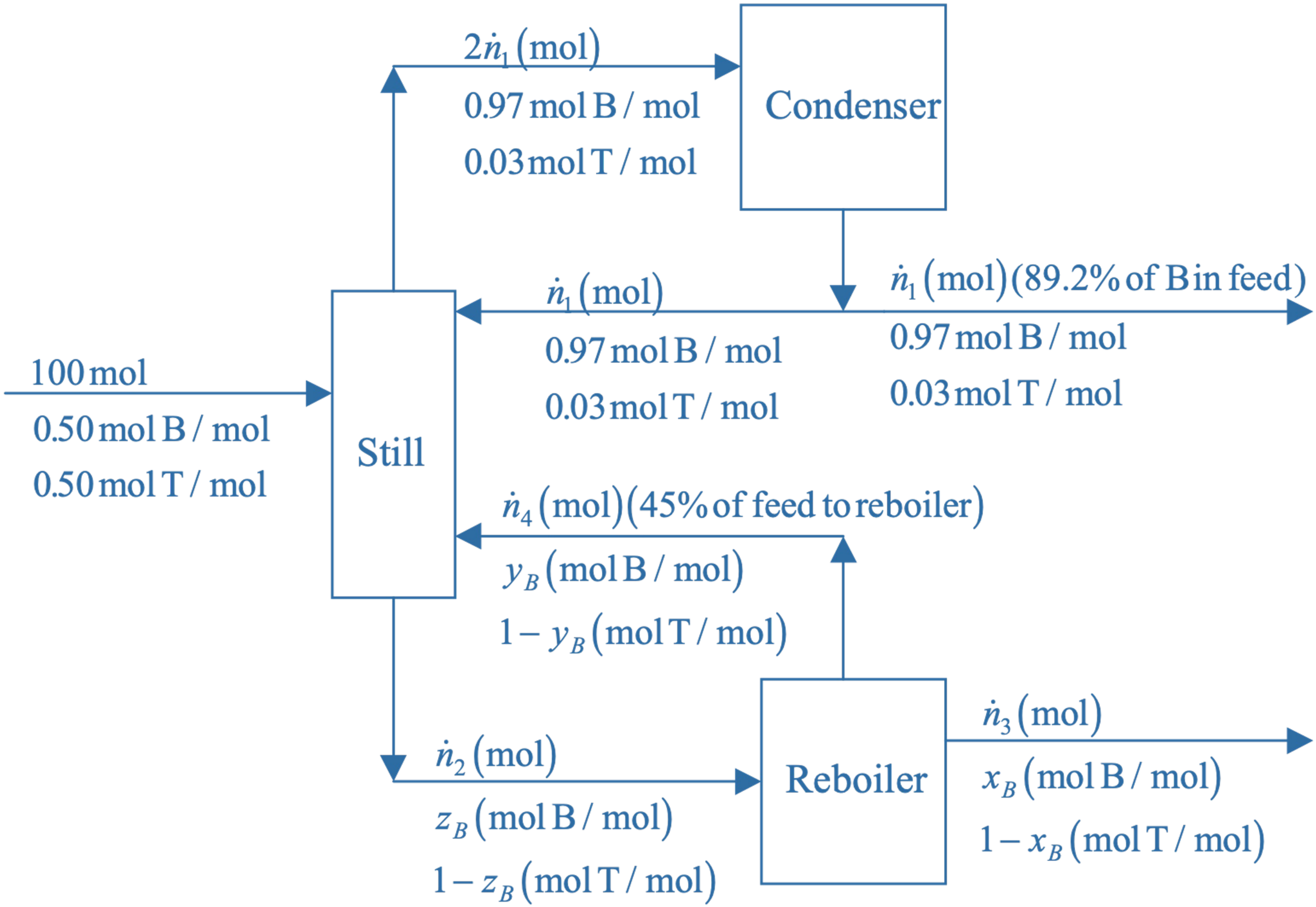
$$\frac{y_B/(1-y_B)}{x_B/(1-x_B)} = 2.25$$

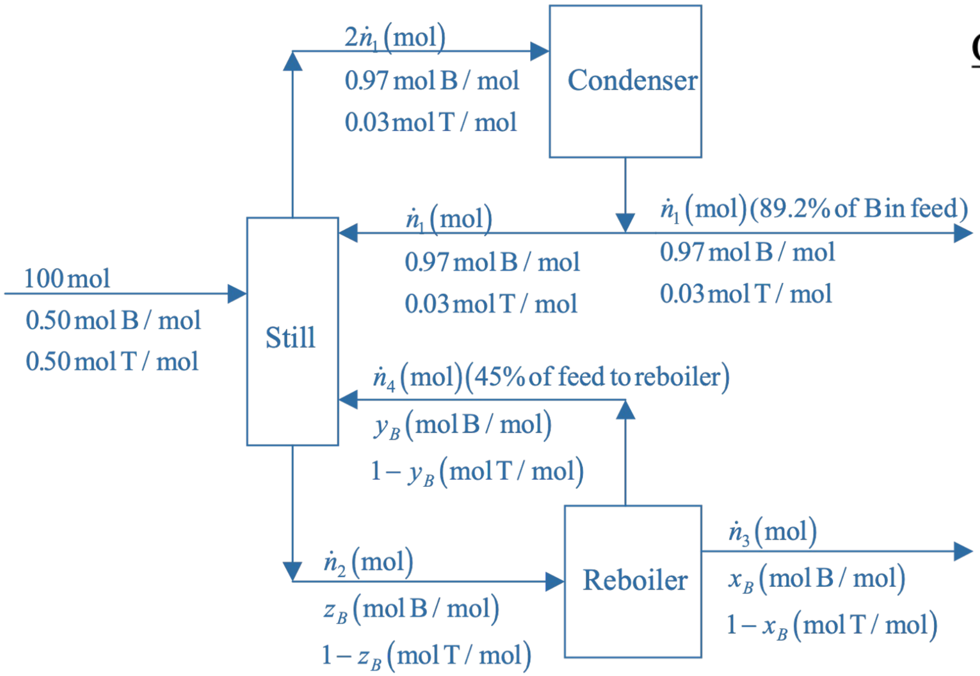
where y_B and x_B are the mole fractions of benzene in the vapor and liquid streams,
respectively.

(a) Take a basis of 100 mol fed to the column. Draw and completely label a flowchart, and for each of four systems (overall process, column, condenser, and reboiler), do the degree-of-freedom analysis and identify a system with which the process analysis might appropriately begin.

(b) Write in order the equations you would solve to determine all unknown variables on the flowchart, highlighting the variable for which you would solve each equation.

(c) Calculate the molar amounts of the overhead and bottoms products, the mole fraction of benzene in the bottoms product, and the percentage recovery of toluene in the bottoms product (moles toluene in bottoms/mole toluene in feed X 100%).


$2\dot{n}_1$ (mol)
0.97 mol B / mol
0.03 mol T / mol
Condenser
$\dot{n}_1$ (mol)(89.2% of B in feed)
0.97 mol B / mol
0.03 mol T / mol
$\dot{n}_1$ (mol)
0.97 mol B / mol
0.03 mol T / mol
100 mol
0.50 mol B / mol
0.50 mol T / mol
Still
$\dot{n}_4$ (mol)(45% of feed to reboiler)
y_B (mol B / mol)
$1-y_B$ (mol T / mol)
$\dot{n}_3$ (mol)
x_B (mol B / mol)
$1-x_B$ (mol T / mol)
$\dot{n}_2$ (mol)
z_B (mol B / mol)
$1-z_B$ (mol T / mol)
Reboiler



Overall process: 3 unknowns ($\dot{n}_1, \dot{n}_3, x_B$)
– 2 balances
– 1 relationship (89.2% recovery)
0 DF

Still: 5 unknowns ($\dot{n}_1, \dot{n}_2, \dot{n}_4, y_B, z_B$)
– 2 balances
3 DF

Condenser: 1 unknown ($\dot{n}_1$)
– 0 balances
1 DF

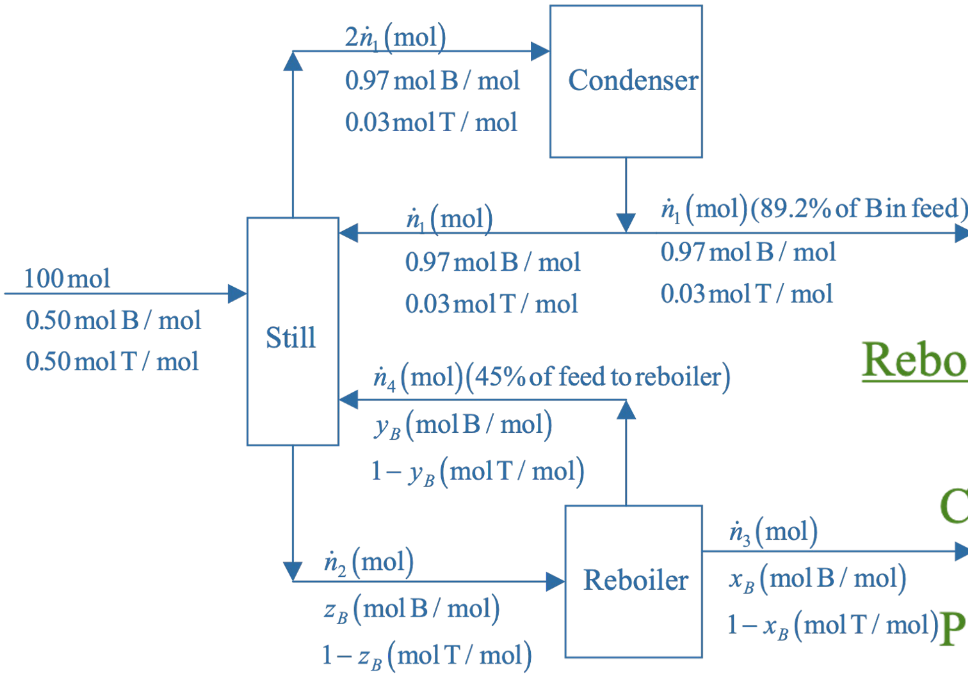
Reboiler: 6 unknowns ($\dot{n}_2, \dot{n}_3, \dot{n}_4, x_B, y_B, z_B$)
– 2 balances
– 2 relationships (2.25 ratio & 45% vapor)
2 DF

Overall process

89.2% recovery: $0.892(0.50)(100) = 0.97\underline{\underline{\dot{n}_1}}$

Overall balance: $100 = \dot{n}_1 + \underline{\underline{\dot{n}_3}}$

B balance: $0.50(100) = 0.97\dot{n}_1 + \underline{\underline{x_B}}\dot{n}_3$



Overall process

89.2% recovery: $0.892(0.50)(100) = 0.97\underline{\underline{\dot{n}_1}}$

Overall balance: $100 = \dot{n}_1 + \underline{\underline{\dot{n}_3}}$

B balance: $0.50(100) = 0.97\dot{n}_1 + \underline{\underline{x_B}}\dot{n}_3$

Reboiler

Composition relationship: $\dfrac{\underline{\underline{y_B}}/\left(1-\underline{\underline{y_B}}\right)}{x_B/\left(1-x_B\right)} = 2.25$

Percent vaporized: $\underline{\underline{\dot{n}_4}} = 0.45\underline{\underline{\dot{n}_2}}$

Mole balance: $\underline{\underline{\dot{n}_2}} = \dot{n}_3 + \underline{\underline{\dot{n}_4}}$

B balance: $\underline{\underline{z_B}}\dot{n}_2 = x_B\dot{n}_3 + y_B\dot{n}_4$

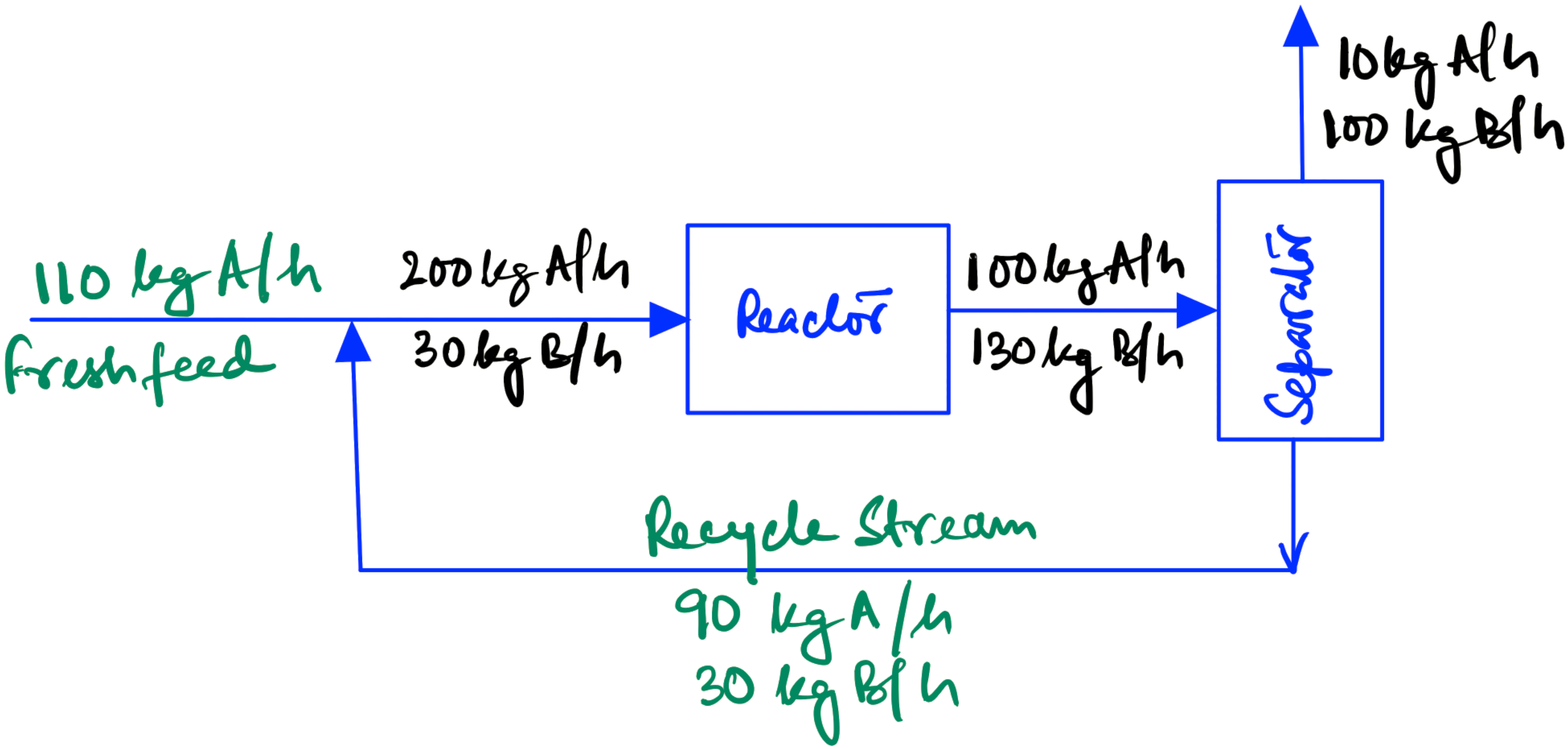
B fraction in bottoms: $x_B = \underline{\underline{0.100\ \text{mol B/mol}}}$

Moles of overhead: $\dot{n}_1 = \underline{\underline{46.0\ \text{mol}}}$

Moles of bottoms: $\dot{n}_3 = \underline{\underline{54.0\ \text{mol}}}$

Recovery of toluene: $\dfrac{\left(1-x_B\right)\dot{n}_3}{0.50(100)} \times 100\% = \dfrac{(1-0.10)(54.02)}{0.50(100)} \times 100\% = \underline{\underline{97\%}}$

Recycle



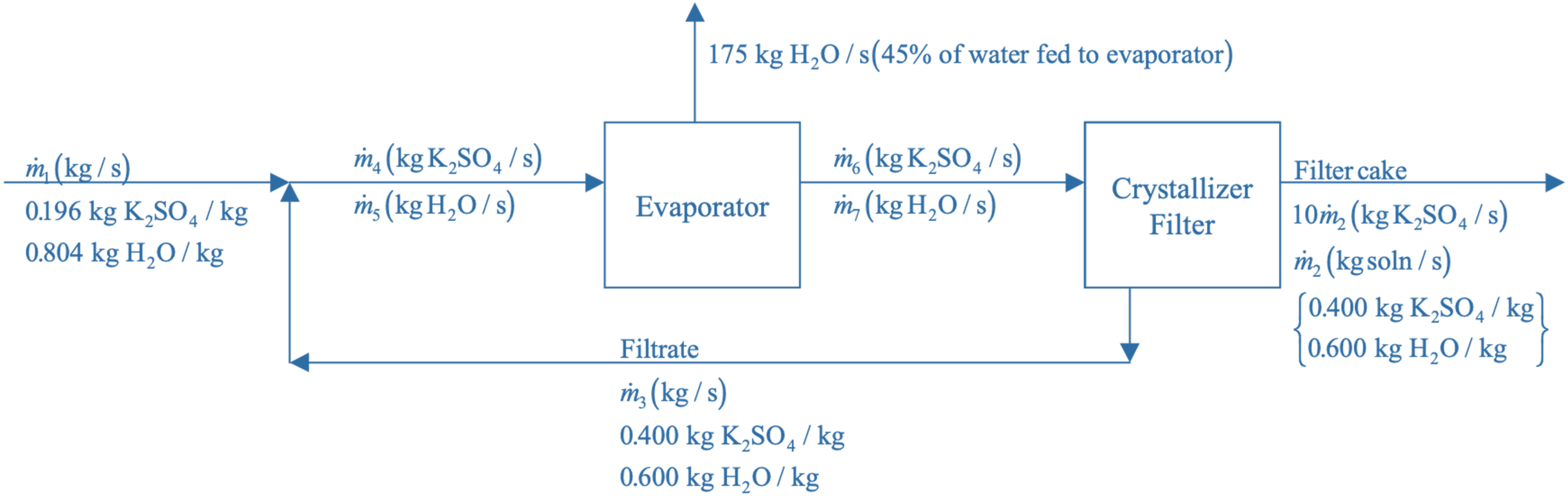
110 kg A/h
fresh feed
200 kg A/h
30 kg B/h
Reactor
100 kg A/h
130 kg B/h
Separator
10 kg A/h
100 kg B/h
Recycle Stream
90 kg A/h
30 kg B/h

An evaporation–crystallization is used to obtain solid potassium sulfate from an aqueous solution of this salt. The fresh feed to the process contains 19.6 wt% K_2SO_4. The wet filter cake consists of solid K_2SO_4 crystals and a 40.0 wt% K_2SO_4 solution, in a ratio 10 kg crystals/kg solution. The filtrate, also a 40.0% solution, is recycled to join the fresh feed. Of the water fed to the evaporator, 45.0% is evaporated. The evaporator has a maximum capacity of 175 kg water evaporated/s.

(a) Assume the process is operating at maximum capacity. Draw and label a flowchart and do the degree-of-freedom analysis for the overall system, the recycle–fresh feed mixing point, the evaporator, and the crystallizer. Then write in an efficient order of the equations that you would solve to determine all unknown stream variables. In each equation, highlight the variable for which you would solve.

(b) Calculate the maximum production rate of solid K_2SO_4, the rate at which fresh feed must be supplied to achieve this production rate, and the ratio kg recycle/kg fresh feed.

(c) Calculate the composition and feed rate of the stream entering the crystallizer if the process is scaled to 75% of its maximum capacity.



Basis of calculation – 175 kg W evaporated/s

Overall process

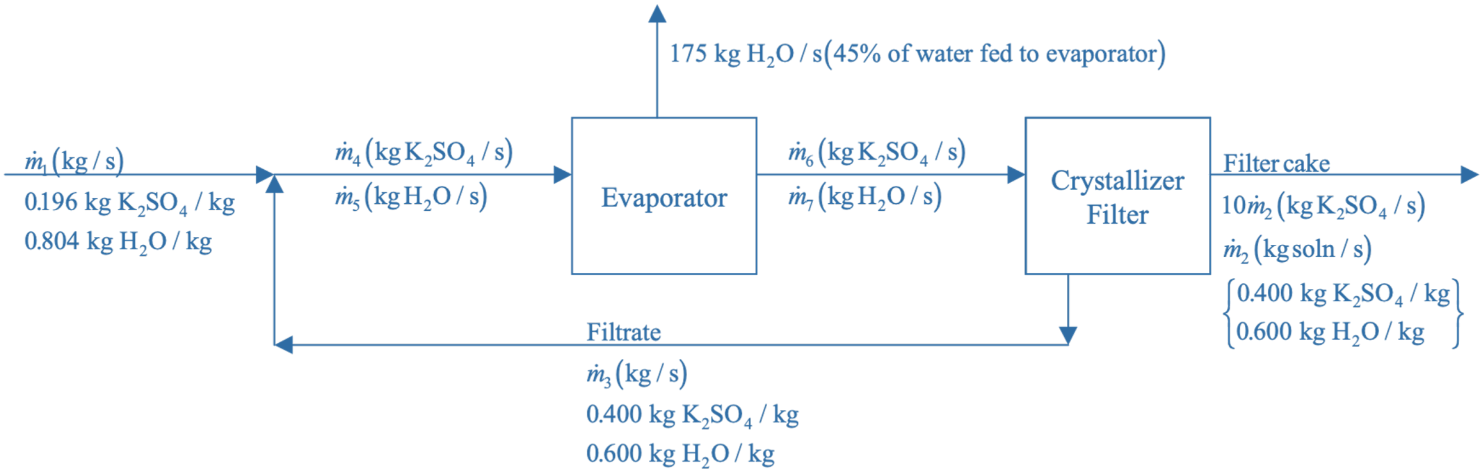
2 unknowns ($\dot{m}_1, \dot{m}_2$)
− 2 balances

0 DOF

Mixing point

4 unknowns ($\dot{m}_1, \dot{m}_3, \dot{m}_4, \dot{m}_5$)
− 2 balances

2 DOF



Evaporator

4 unknowns ($\dot{m}_4, \dot{m}_5, \dot{m}_6, \dot{m}_7$)
− 2 balances
− 1 % evaporation

1 DOF

Crystallizer

4 unknowns ($\dot{m}_2, \dot{m}_3, \dot{m}_6, \dot{m}_7$)
− 2 balances

2 DOF

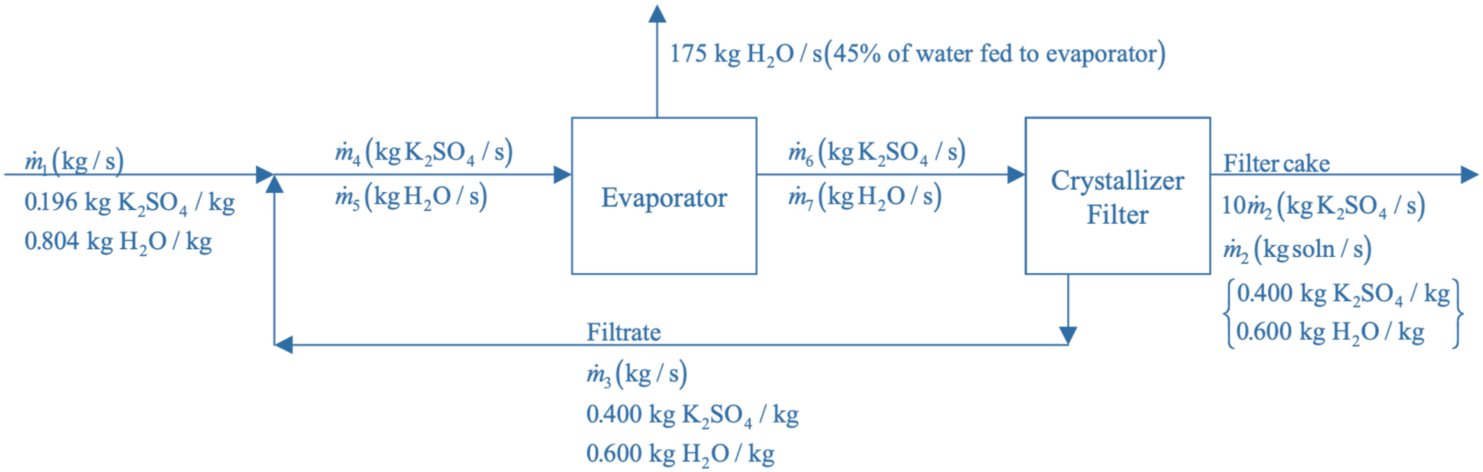
Overall balance

→ mass
→ component $\Big\}$ $\dot{m}_1, \dot{m}_2$

% evaporation
⇒ $\dot{m}_5$

Mixing point balance

→ mass
→ component $\Big\}$ $\dot{m}_3, \dot{m}_4$



% evaporation

$$175 \text{ kg/s} = 0.450 \, \dot{m}_5$$

Evaporator balance

→ K balance

→ W balance

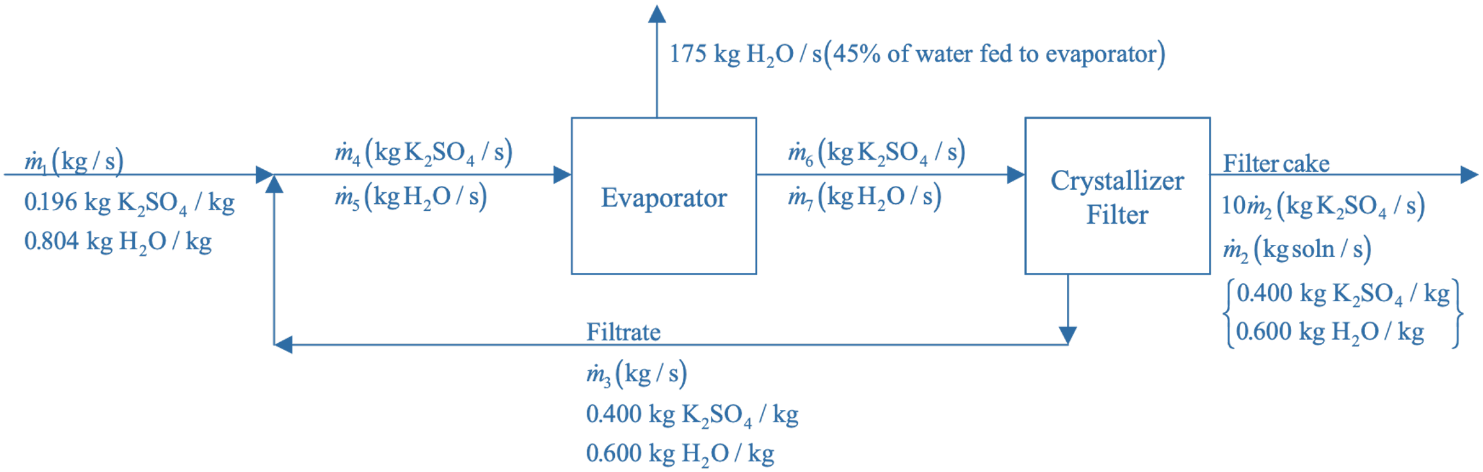
$\Big\}$ $\dot{m}_6, \dot{m}_7$

Overall mass balance

$$\dot{m}_1 = 175 + 10\dot{m}_2 + \dot{m}_2$$

Overall K balance

$$0.196 \, \dot{m}_1 = 10\dot{m}_2 + 0.400 \, \dot{m}_2$$



Mixing point – W balance

$$0.804\,\dot{m}_1 + 0.600\,\dot{m}_3 = \dot{m}_5$$

Mixing point – mass balance

$$\dot{m}_1 + \dot{m}_3 = \dot{m}_4 + \dot{m}_5$$

Evaporator – K balance

$$\dot{m}_6 = \dot{m}_4$$

Evaporator – W balance

$$\dot{m}_5 = 175 + \dot{m}_7$$

Fresh feed rate

$\rightarrow \dot{m}_1$ kg/s

Production rate

$\rightarrow 10\dot{m}_2$ kg K/s

Recycle ratio

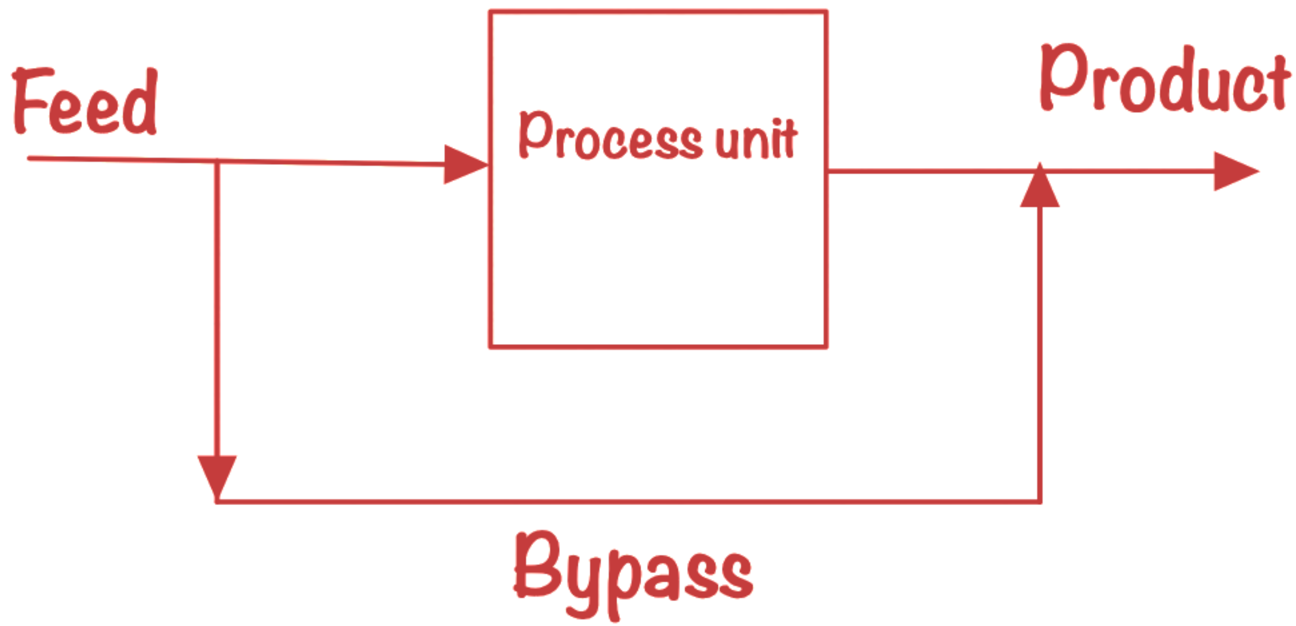
$\rightarrow \dfrac{\dot{m}_3}{\dot{m}_1}\ \dfrac{\text{kg recycle}}{\text{kg fresh feed}}$

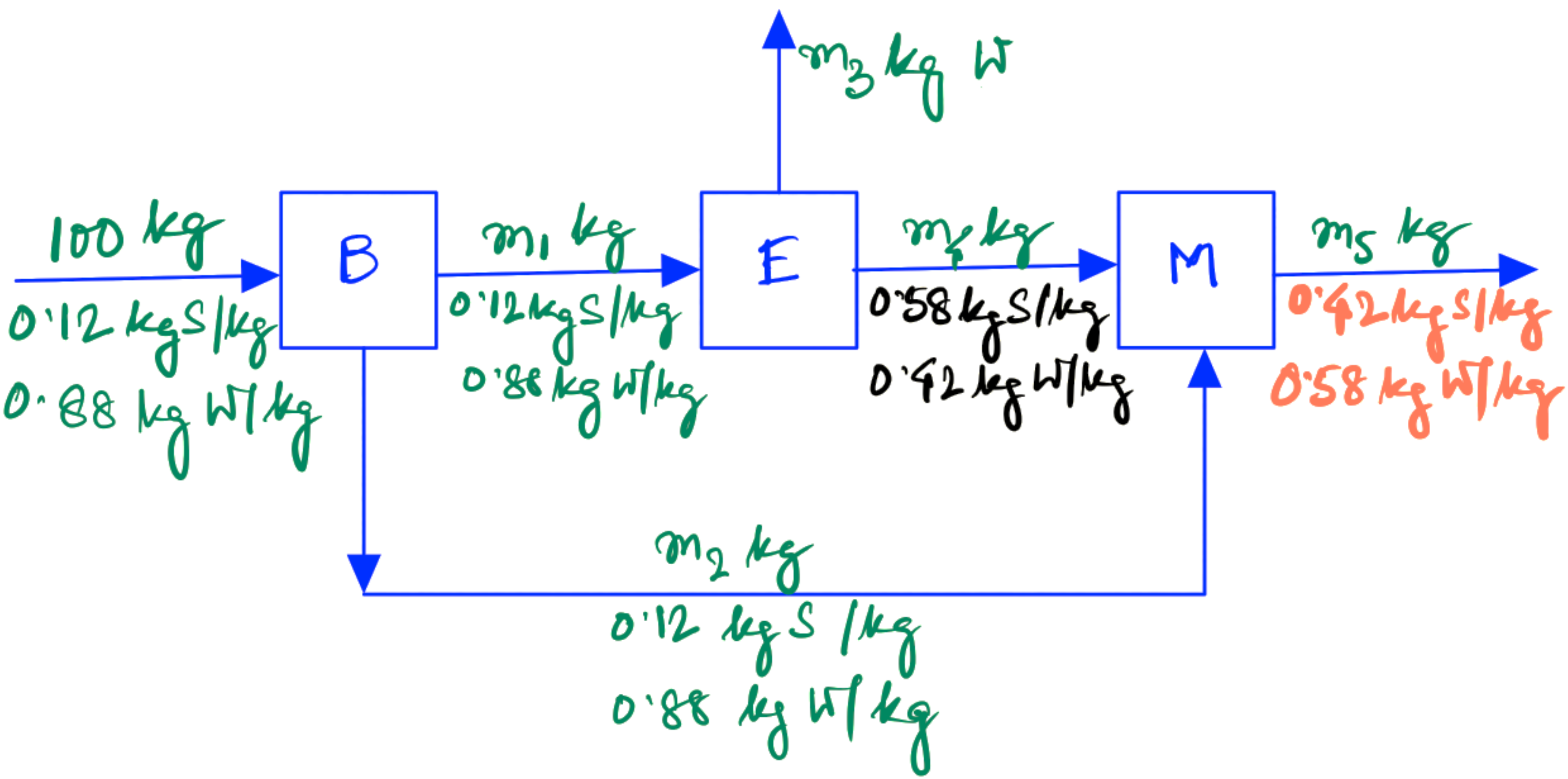
SCALING

Fresh orange juice contains 12.0 wt% solids and the balance water, and concentrated orange juice contains 42.0 wt% solids. Initially a single evaporation process was used for the concentration, but volatile constituents of the juice escaped with the water, leaving the concentrate with a flat taste. The current process overcomes this problem by bypassing the evaporator with a fraction of the fresh juice. The juice that enters the evaporator is concentrated to 58 wt% solids, and the evaporator product stream is mixed with the bypassed fresh juice to achieve the desired final concentration.

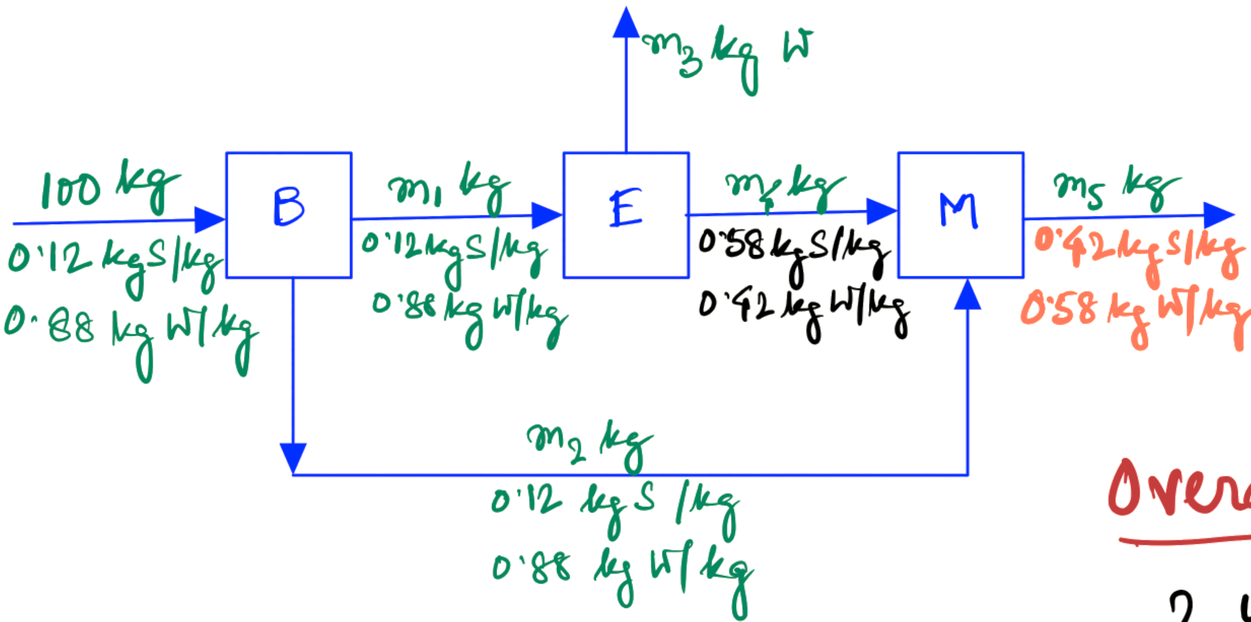
(a) Draw and label a flowchart of this process, neglecting the vaporization of everything in the juice but water. Then perform the degree-of-freedom analysis for the overall system, the evaporator, and the bypass–evaporator product mixing point, and write in order the equations you would solve to determine all unknown stream variables. In each equation, highlight the variable for which you would solve.

(b) Calculate the amount of product (42% concentrate) produced per 100 kg fresh juice fed to the process and the fraction of the feed that bypasses the evaporator.


Feed
Process unit
Product
Bypass



100 kg
0'12 kg S/kg
0'88 kg W/kg
B
m1 kg
0'12 kg S/kg
0'88 kg W/kg
E
m3 kg W
m4 kg
0'58 kg S/kg
0'42 kg W/kg
M
m5 kg
0'42 kg S/kg
0'58 kg W/kg
m2 kg
0'12 kg S /kg
0'88 kg W/kg



Overall process

2 unknowns (m_3, m_5)

$-$ 2 balances

0 DOF

Bypass

2 unknowns (m_1, m_2)

$-$ 1 balance

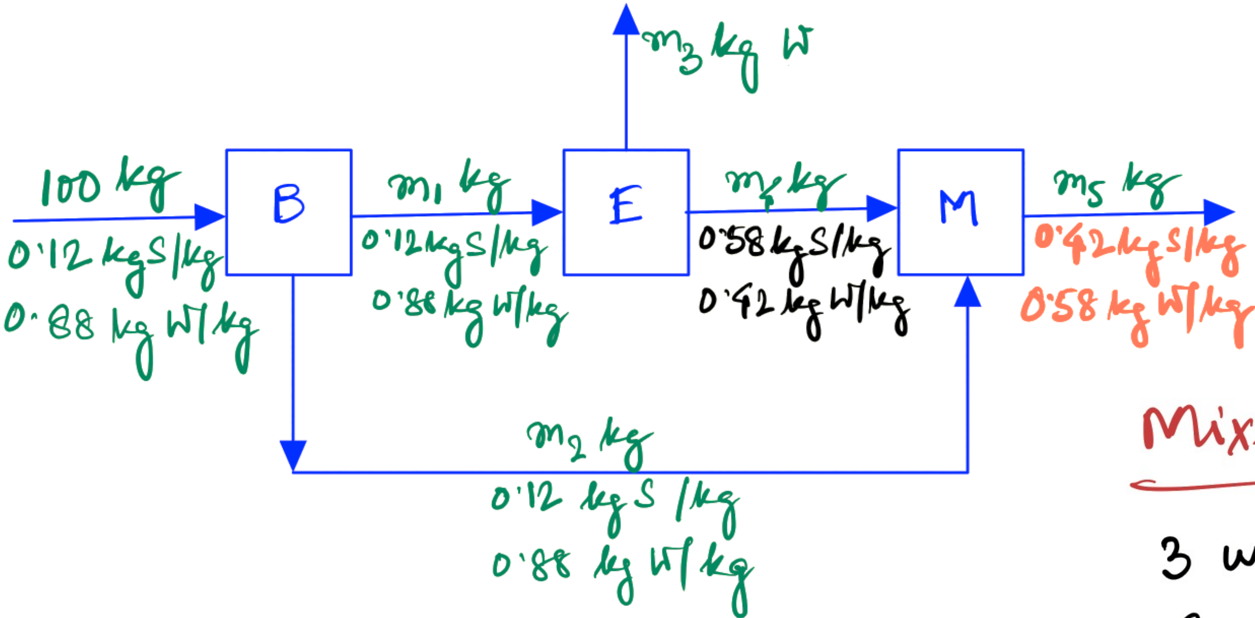
1 DOF

Evaporator

3 unknowns (m_1, m_3, m_4)

$-$ 2 balances

1 DOF



Mixing point

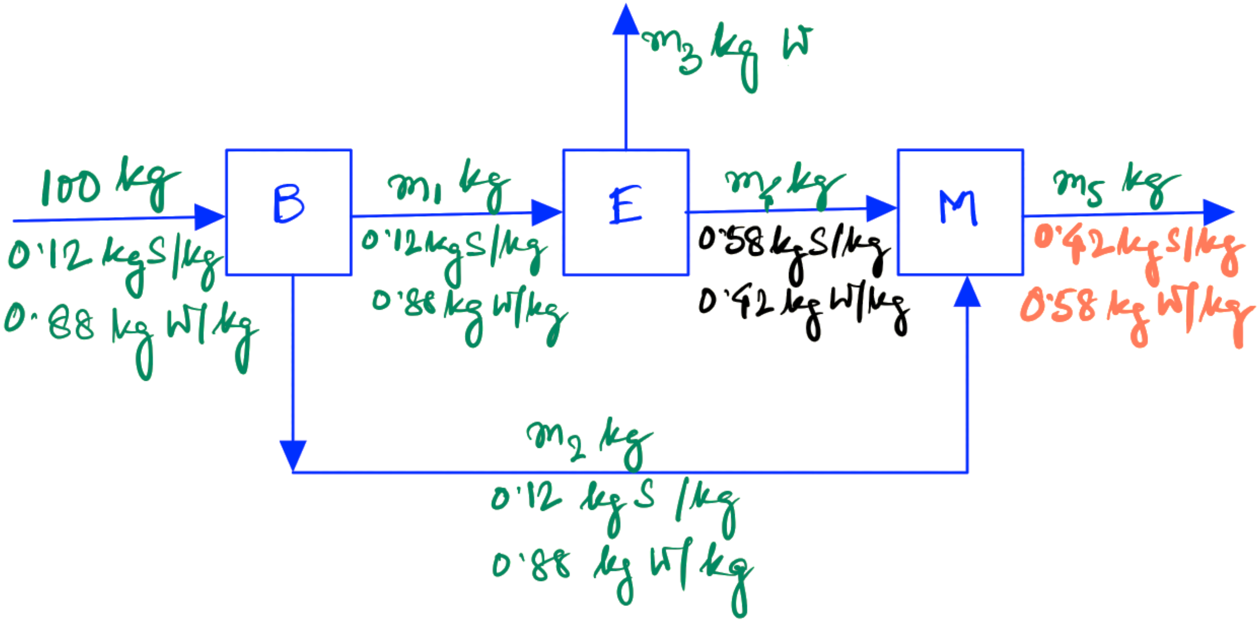
3 unknowns (m_2, m_4, m_5)
− 2 balances
1 DOF

Overall S : $0.12 \times 100 = 0.42 \times m_5$

〃 mass : $100 = m_3 + m_5$

Mixing point mass: $m_4 + m_2 = m_5$

〃 S : $0.58\, m_4 + 0.12\, m_2 = 0.42\, m_5$



Bypass mass : $100 = m_1 + m_2$

Answer : m_5

Bypass fraction : $\frac{m_2}{100}$