University of Melbourne
Department of Chemical Engineering
CHEN20010 MATERIAL AND ENERGY BALANCES
EXERCISE SHEET C
BLOCK FLOW DIAGRAMS AND MATERIAL BALANCES

1. Prepare a block flow diagram based upon the following process description. A stream containing a mixture of benzene, toluene and xylene is fed to a distillation column. This column separates the stream into a stream rich in benzene and lean in xylene which leaves the top of the column, and another stream which is rich in toluene and xylene and leaves the base of the column. This second product stream is mixed with a stream containing toluene and xylene to produce a stream which contains mostly xylene.

2. Nitric oxide may be prepared by the oxidation of ammonia:

$$4\ NH_3 + 5\ O_2 \rightarrow 4\ NO + 6\ H_2O$$

Based upon the following description prepare a block flow diagram for the process. Separate streams containing ammonia and oxygen are mixed and fed into a reactor in which all the ammonia is consumed in the above reaction to produce nitric oxide and water. Because more oxygen is fed to the reactor than is needed to consume all the ammonia, some oxygen leaves the reactor in the product stream with the nitric oxide and water. The reactor effluent flows into a condenser which separates the water from the nitric oxide and oxygen gases. The product stream leaving the condenser contains only nitric oxide and oxygen while the waste water stream contains only water.

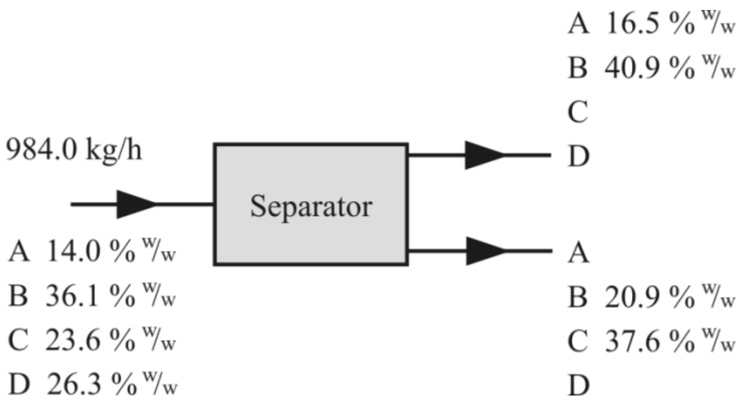
3. Cumene is the name given to isopropylbenzene, a colourless liquid used in the production of phenol and acetone. Based upon the description below prepare a block flow diagram for the production of cumene from benzene, propylene and propane. Fresh feed streams of benzene and propylene are mixed together before being introduced into a reactor. Pure propane is fed directly into the reactor. Within the reactor cumene and other polyalkylated benzene compounds are formed by the reactions of benzene with the propylene and the propane. The effluent stream from the reactor containing the unreacted reactants and the reaction products then passes to a separator in which all the unreacted propane is removed. The remaining material passes to a second separator in which all the unreacted benzene as well as some of the unreacted propylene is removed. The remaining material then passes to the final separator in which the cumene is separated from the remaining polyalkylated benzene compounds.

4. Formaldehyde may be produced by the partial oxidation of methane with oxygen:

$$CH_3OH + \tfrac{1}{2}\,O_2 \rightarrow HCHO + H_2O$$

Based upon the following description prepare a block flow diagram for the process. A feed stream containing methanol is mixed with an air feed stream and a recycle stream containing oxygen and nitrogen. The resulting mixed stream enters the reactor in which all the methanol is consumed to produce formaldehyde and steam. Some of the oxygen is also consumed. The effluent from the reactor enters a separator. A feed stream containing pure water also enters the separator. A solution of formaldehyde in water leaves the base of the separator while the nitrogen and unreacted oxygen leave the top of the unit. This overheads stream is split with a portion being purged while the remainder forms the recycle stream referred to earlier.

5. A stream containing four components flows at a rate of 984.0 kg/hr into a separator. The separator produces two streams of differing compositions. The upper product stream has a composition of 16.5 % $^{w}/_{w}$ A and 40.9 % $^{w}/_{w}$ B with C and D making up the remainder. The lower product stream contains all four components but only the weight percentages of B and C are known. All available data is presented below. Calculate the compositions and flow rates of the two product streams.



Text alternative of flow diagram for question 5:

- A stream enters a separator with an overall flow rate of 984.0 kilograms per hour.
- All percentages are given in w per w, or weight concentration.
- The stream comprises 14.0 percent component A, 36.1 percent component B, 23.6 percent component C, and 26.3 percent component D.
- The separator produces an upper product stream and a lower product stream.
- The upper product stream has a composition of 16.5 percent A and 40.9 percent B, with unspecified amounts of C and D making up the remainder.
- The lower product stream has a composition of 20.9 percent component B and 37.6 percent component C, with unspecified amounts of A and D making up the remainder.
- The flow rates of the two product streams are not given.

6. Milk with any desired fat content may be produced by blending different ratios of skim milk and cream. If the skim milk has a fat content of 0.090 % $^w/_w$ and the cream contains 34.2 % $^w/_w$ fat, then how much of each of these must be blended together to produce 2.00 kg of milk having a fat content of 3.95 % $^w/_w$?

7. Wet paper pulp contains 36.0 % $^w/_w$ water. This pulp is to be processed in a drier (i.e water is to be removed) to produce a pulp containing 11.0 % $^w/_w$ water. If the wet pulp enters the drier at a rate of 3524 kg/h, calculate the production rate of the dried pulp and the rate of removal of water (kg/h) ?

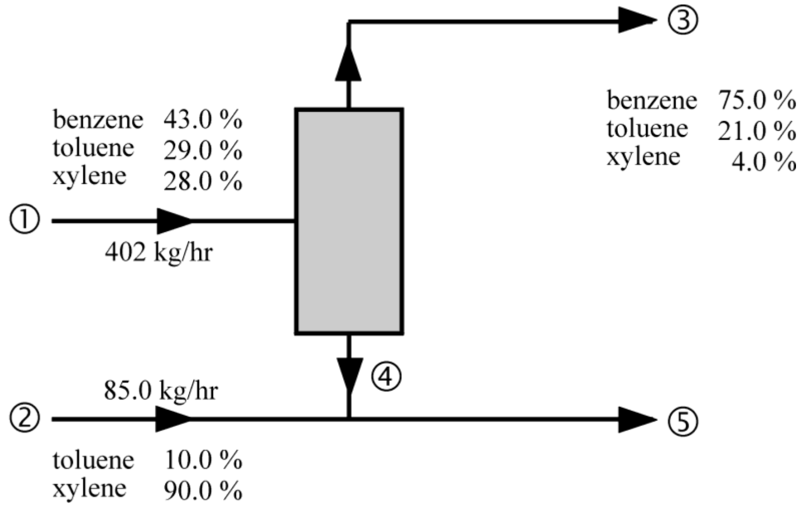
8. The spent acid from a nitrating process contains 43.0 % $^w/_w$ H_2SO_4, 36.0 % $^w/_w$ HNO_3, balance H_2O. This acid to be strengthened for re-use by the addition of concentrated sulphuric acid (91.0 % $^w/_w$ H_2SO_4, balance H_2O) and concentrated nitric acid (88.0 % $^w/_w$ HNO_3, balance H_2O). The resulting mixed acid is to contain 40.0 % $^w/_w$ H_2SO_4 and 43.0 % $^w/_w$ HNO_3. Calculate the quantities (kg) of spent and concentrated acids which should be mixed to yield 1000.0 kg of mixed acid.

9. A slurry containing solids suspended in water is flowing through a pipeline at a rate of 30.4 kg/min. The slurry then enters a trap in which some of the solids are captured and retained. If the slurry initially contains 32.1 % $^w/_w$ solids and the rate of accumulation of solids within the trap is 0.080 kg/sec, what are the composition and flow rate of the slurry after it leaves the trap? Assume water accumulates in the trap at a rate of only 0.0050 kg/sec.

10. A distillation column in an oil refinery, operating continuously, is supplied with an input feed stream of the composition given below at the rate of 18900 kg/h. There are two product (output) streams from the column, the distillate and the residue and incomplete analyses of these are given below. Assuming steady state operation, determine the flow rates (as kg/h and as kmol/h) of the distillate and residue and the complete composition (mol %) of the residue. (Note : There is no chemical reaction in the system).

Component			Analysis - mol %		
		MW	Feed	Distillate	Residue
iso-butane	C_4H_{10}	58	32.1	82.4	
n-butane	C_4H_{10}	58	47.1	16.3	51.9
iso-pentane	C_5H_{12}	72	19.1	1.3	
iso-hexane	C_6H_{14}	86	1.7		

11. A stream containing a mixture of benzene, toluene and xylene is fed to a distillation column at a rate of 402 kg/h. This column separates the stream into a stream rich in benzene and lean in xylene which leaves the top of the column, and another stream which is rich in toluene and xylene and leaves the base of the column. This second product stream containing 39 % toluene is mixed with a stream flowing at a rate of 85.0 kg/h containing toluene and xylene only.



Calculate the flow rate of stream ③ and the composition of stream ⑤.

Text alternative of flow diagram for question 11: • Stream 1 has a flow rate of 402 kilograms per hour, and is composed of 43.0 percent benzene, 29.0 percent toluene, and 28.0 percent xylene. • Stream 1 feeds into a distillation column, which produces streams 3 and 4. • Stream 3 is composed of 75.0 percent benzene, 21.0 percent toluene and 4.0 percent xylene. • The flow rate of stream 3 is not given. • Stream 2 has a flow rate of 85.0 kilograms per hour. It has a composition of 10.0 percent toluene and 90.0 percent xylene. • Stream 4 combines with stream 2 to produce stream 5. • The composition of stream 5 is not given.

12. Absolute alcohol (pure ethanol) may be produced from industrial alcohol (ethanol and water) by a process known as azeotropic distillation, using a third component (called an "entrainer") such as benzene. The industrial alcohol is fed to a tall distillation column, (at an intermediate level), to the top of which is also fed a benzene-rich stream, commonly called "reflux". The vapour stream ("overhead") leaving the top of the column is a three component mixture (an "azeotrope") containing benzene, ethanol and water while the liquid product leaving the bottom of the column (the "bottoms") is pure ethanol. The "overhead" vapour stream passes to a condenser which condenses it completely to liquid. This liquid is in fact two separate immiscible phases which are separated in a decanter into an upper layer (benzene-rich) which is mixed with pure benzene as make-up for losses, and fed to the top of the column as the reflux stream. The lower layer, rich in ethanol and water, is sent to another unit for benzene recovery.

Analysis, % w/w

	Feed	Bottoms Product	Overhead Vapour	Upper Layer	Lower Layer	Make-up
Ethanol	95.0	100.0	18.5	16.3	39.8	-
Water	5.0		7.5	2.7	54.3	-
Benzene			74.0	81.0	5.9	100.0

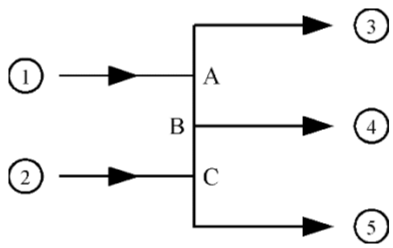
For a feed rate to the process of 1200 kg/h, calculate:

a) Production rate of absolute alcohol (kg/h).
b) Percentage recovery of ethanol from feed as pure alcohol.
c) Benzene required as make-up (kg/h).
d) Rate of production of upper and lower layers in the decanter (kg/h).

13. A stream of skim milk with a fat content of 0.070 % on a weight basis is mixed with a stream of cream having a fat content of 37 %. The resultant milk stream then passes to a heat exchanger for pasteurisation. This product stream has a fat content of 3.82 %. If the volumetric flow rate of the skim milk is 17,600 L/hr, what are the volumetric flow rates of the cream stream and the milk stream leaving the mixer ?

ρ (cream) = 0.971 kg/L
ρ (skim milk) = 1.022 kg/L
ρ (product milk) = 1.020 kg/L

14. Streams 1 to 5 are connects as shown in the diagram below. A, B and C are either simple splitters or mixers. The directions of flow in streams AB and BC are unknown.



The following information is known:

i) Stream 1 has a flow rate of 12 kg/min and a composition of 66 % w/w CH_3OH, 8 % w/w C_2H_5OH, balance water.
ii) Stream 2 has a flow rate of 17 kg/min and a composition of 18 % w/w CH_3OH, 18 % w/w C_2H_5OH, balance water.
iii) Stream 3 has the same composition as stream 1.
iv) The combined flow rates of streams 3 and 4 together total less than the flow rate of stream 1.
v) Stream 5 contains 28 % w/w CH_3OH.
vi) The flow rate of stream 3 is one-third that of stream 5.

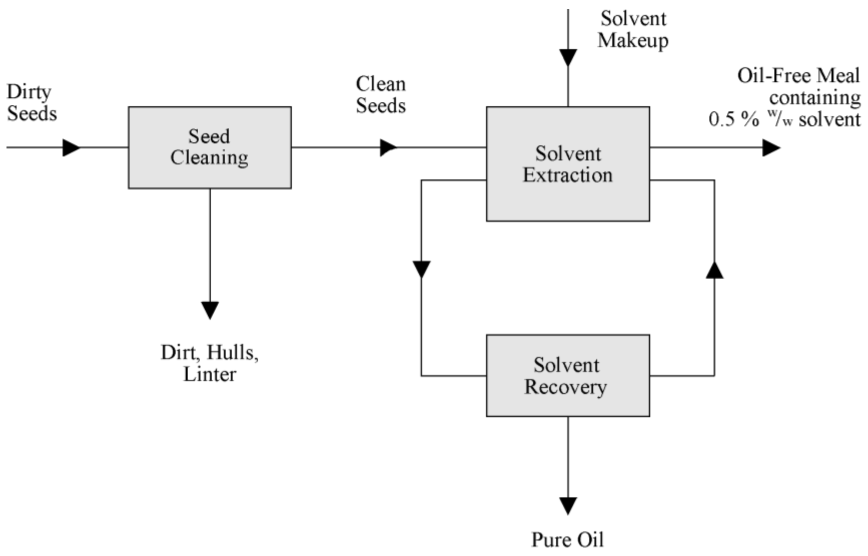
a) In which directions do streams AB and BC flow ?

b) What are the mass flow rates of streams 3, 4 and 5 (kg/min) ?

Text alternative of graphic for question 14:

- Streams 1 and 2 flow into A, B and C, which are either splitters or mixers.
- The direction of flow of AB and BC are not shown.
- A produces stream 3.
- B produces stream 4.
- C produces stream 5.
- No other information is given in the image. All other information is given in the text of the question.

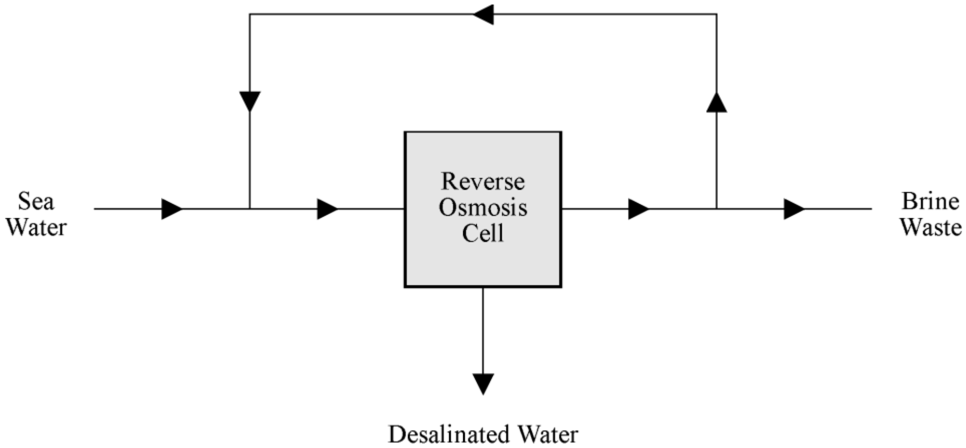
15. Oilseed protein sources include soybean, cottonseed, peanut, sunflower, copra, rapeseed, sesame, safflower, castor and flax. Commonly, the separation of the oil from the protein meal is performed by solvent extraction. The analysis of cottonseed on a weight basis is 4 % hull, 10 % linter, 37 % meal and 49 % oil. During the extraction step, about 2 lb of solvent (in this case hexane) must be used per 1 lb of clean seeds processed. For each tonne of raw seeds to be processed, determine the amount of oil and oil-free meal produced and the amount of hexane that must be recycled through the solvent extraction unit.



Text alternative of graphic for question 15:

- Dirty seeds are fed into a seed cleaning process.
- The seed cleaning process produces one stream of dirt, hulls and linter, and another stream of clean seeds.
- The clean seeds are fed into solvent extraction along with the solvent.
- Solvent extraction produces an oil-free meal as well as pure oil via a solvent recovery process.
- The oil-free meal contains 0.5 percent weight per weight of the solvent.
- The solvent recovery process recycles the solvent while producing the oil.
- No other information is given in the image. All of the other information is in the text of the question.

16. Seawater may be desalinated (i.e. have the salt removed) by passing it through a reverse osmosis cell. The diagram below shows a typical system in which sea water with a salt content of 3.1 % $^w/_w$ is mixed with recycled brine (high-salt-content water) and fed to a reverse osmosis cell. Desalinated water with a salt content of 500 ppm (0.05 %$^w/_w$) leaves the cell along with a concentrated stream containing 5.25 % $^w/_w$ salt. Part of this concentrated stream is recycled back to be mixed with the sea water.

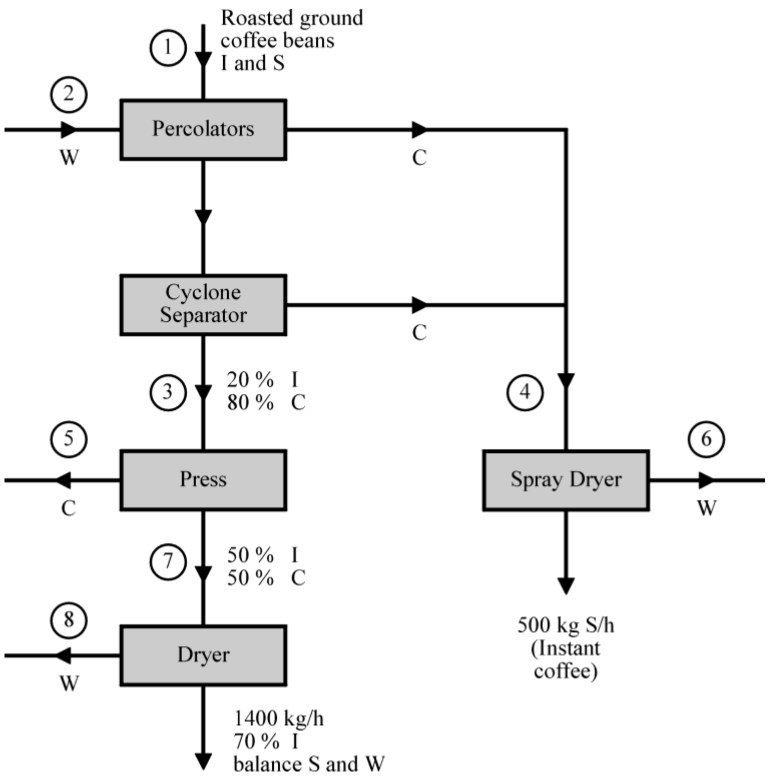


Text alternative of graphic for question 16: • A mixture of sea water and recycled brine enters a reverse osmosis cell. • The reverse osmosis cell produces desalinated water as well as brine. • Some of the brine is discarded and some of it is recycled into the original stream of seawater.

If the flowrate of the sea water into the system is 1000 lb/h, and the water entering the cell is 4.0 % $^w/_w$ salt, calculate:

a) the flowrate into the cell,
b) the flowrate of desalinated water from the cell,
c) the flowrate of brine waste.

17. Coffee beans contain components that are soluble in water and others that are not. Instant coffee is produced by dissolving the soluble portion in boiling water (i.e, by making coffee) in large percolators, then feeding the coffee to a spray dryer in which the water is evaporated, leaving the soluble coffee as a dry powder. The insoluble portion of the coffee beans (the spent grounds) passes through several drying operations, and the dried grounds are either burned or used as landfill. The solution removed from the grounds in the first stage of the drying operation is fed to the spray dryer to join the effluent from the percolators. The symbols S and I denote the soluble and insoluble components of the coffee beans, W is water and C is a solution containing 35%^{w}/w S and 65%^{w}/w W. Calculate the flow rates (kg/h) of streams 1 to 8 given the additional information supplied on the flowchart.



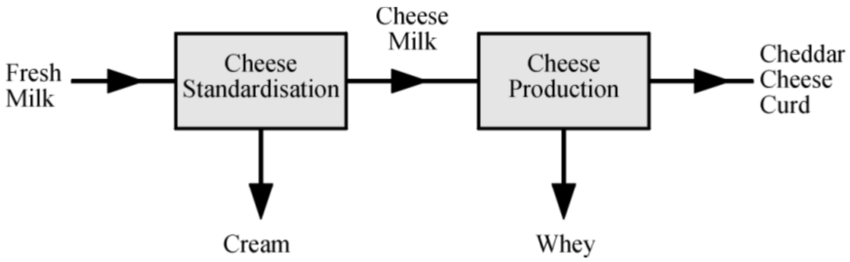
Text alternative version of the flow chart for question 17:

- Stream 1 consists of coffee beans, both soluble (S) and insoluble (I).
- Stream 2 is boiling water.
- Streams 1 and 2 enter percolators.
- From the percolators, two un-numbered streams emerge: One is the solution (C), which is fed straight to a spray dryer. The other is the insoluble portion (I), which is then fed into a cyclone separator.
- The cyclone separator produces Stream 3 – see below – and a second stream with more of the solution C. The solution C is fed into the spray dryer along with the original C solution from the percolators. This combined stream of the solution C entering the spray dryer is Stream 4.
- The spray dryer then produces 500kg S per hour – that is, instant coffee.
- The spray dryer also produces an unspecified amount of water as stream 6.
- Returning to Stream 3: Stream 3 is a mixture of 20 percent I and 80 percent C emerging from the cyclone separator and entering a press.
- The press then produces stream 5 and stream 7.
- Stream 5 is an unspecified amount of the solution C.
- Stream 7 is 50 percent I and 50 percent C, emerging from the press and entering a dryer.
- The dryer produces stream 8, which is an unspecified amount of water.
- The dryer also produces 1400 kg per hour of a mixture containing 70 percent I and the balance of S and W.

18. Cheddar cheese is manufactured from fresh milk in what is essentially a two-step process. In the first step, fresh milk containing, 3.4 % protein, 4.1 % fat, and 13.0 % total solids is fed to a separator for fat standardisation which produces cheese milk and cream. The cream has a composition of 42.0 % fat, 1.9% % protein, 48.0 % total solids. The production of cheddar cheese requires the ratio of protein to fat in the cheese milk to be 0.88.

The cheese milk is fed to the second stage in which the cheese is formed and separated from the whey. The cheddar cheese has a composition of 26 % protein, 33 % fat and 36% moisture. Eighty percent of the protein in the cheese milk leaves the second unit as part of the cheese.

Note: All compositions are expressed on a weight basis. Total solids includes protein and fat content. Each stream contains protein, fat, other non-protein, non-fat solids and moisture.



Calculate:

a) the mass of cheese milk produced per kilogram of fresh milk processed
b) the mass of cheese produced per kilogram of fresh milk processed
c) the composition (fat, protein and total solids) of the whey.

Text alternative of graphic for question 18:

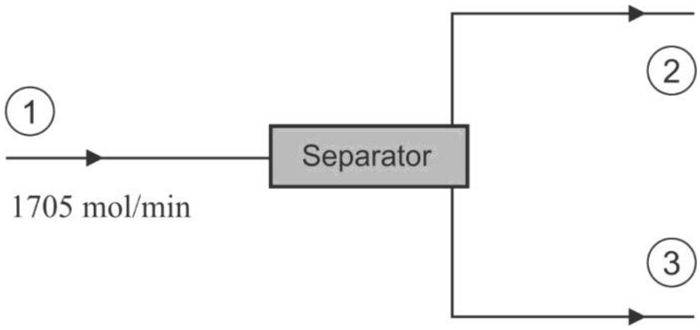
- Fresh milk is fed into cheese standardisation.
- Cheese standardisation produces cream and cheese milk.
- Cheese milk is fed into cheese production, which in turn produces whey and cheddar cheese curd.
- No other information is given in the image – it's in the text of the question.

19. Potassium nitrate (KNO_3) crystals are to be recovered from solution, supplied at a rate of 4,503 kg/h, which contains as solutes 18.2% $^w/_w$ KNO_3 and 0.5% $^w/_w$ of an impurity X, while the balance is water. This feed solution is mixed with a recycle stream containing 35.2% $^w/_w$ KNO_3 and 9.8% $^w/_w$ X, balance water, and fed to an evaporator where pure water is boiled off to produce a solution containing 45.0% $^w/_w$ KNO_3. This hot solution passes to cooling crystallizer (causing crystals of KNO_3 to come out of solution, X is soluble and remains in solution). The slurry of KNO_3 crystals is then filtered to produce a clear filtrate, containing 35.2% $^w/_w$ KNO_3 which becomes the recycle stream referred to above. The filter cake consists of KNO_3 crystals and a solution of the same composition as the filtrate (or recycle stream). The content of solution in this filter cake is 3.0 kg per 100 kg of dry KNO_3 crystals. The impurity X, although soluble, if allowed to accumulate in the system because of the recycle will eventually interfere with the crystallization process. To prevent this, part of the recycle stream is split off, as a purge stream and sent to waste. The rate of flow of this purge stream is adjusted so that under steady state conditions the concentration of X in this recycle stream is 9.8% $^w/_w$.

a) Draw the block flow diagram for the process.
b) Calculate the composition of the filter cake and express the answer in % $^w/_w$.
c) Calculate the flow rate (kg/h) of the purge stream.
d) Calculate the percentage loss of KNO_3 in the purge stream.
e) Calculate the flow rate (kg/h) of the recycle stream.

MATLAB EXERCISES – Use MATLAB to answer these problems

M20. A feed stream to a separator flows at a rate of 1705 mol/h with a composition of 42.1 mol % A, 11.3 mol % B, 22.5 mol % C and 24.1 mol % D. This feed stream is stream ①. The two streams that leave the separator – streams ② and ③ – leave at the same temperature.



α_A is the ratio of the number of moles of A leaving the separator in stream ② to the number of moles of A leaving in stream ③. So,

$$\alpha_A = \frac{\text{moles A in ②}}{\text{moles A in ③}}$$

Also,

$$\alpha_B = \frac{\text{moles B in ②}}{\text{moles B in ③}}$$

α_C and α_D are defined in a similar manner.

a) At 75.0°C, $\alpha_A = 0.981$, $\alpha_B = 0.752$, $\alpha_C = 1.383$ and $\alpha_D = 0.753$.

Calculate the flow rates and compositions of streams ② and ③.

b) In reality, the values of α_A, α_B, α_C and α_D vary with the operating temperature of the separator. We know that

$\alpha_A = 0.550 + 0.003500\ T + 0.00003000\ T^2$

$\alpha_B = 0.136 + 0.00001000\ T + 0.0001093\ T^2$

$\alpha_C = 1.321 + 0.0005650\ T + 0.000003450\ T^2$

$\alpha_D = 0.521 + 0.0008950\ T + 0.00002935\ T^2$

Here, T is the operating temperature in °C.

To the nearest 0.1°C, determine the temperature at which the total molar flow rates of streams ② and ③ are equal.

Text alternative of image for question M20: • Stream 1 enters the separator at a flow rate of 1705 mol/min. • Streams 2 and 3 leave the separator. • No other information is given in the image.

M21. In offshore oil and gas platforms, and in floating production facilities, seawater is often used as a cooling fluid in place of conventional freshwater. The seawater is withdrawn from the ocean, usually at a depth of several metres, and then later discharged back into the ocean at a higher temperature. The density of the seawater will vary with not only its temperature and pressure, but also its salinity. Typically, the salinity of ocean seawater, near the surface (also known as surface water) will be around 35 g/kg. The temperature of surface water can vary between 25°C to just -2°C in the Arctic and Southern Oceans.

The density of seawater may be predicted using the equation:

$$\begin{aligned}\rho = {} & a_1 + a_2 t + a_3 t^2 + a_4 t^3 + a_5 t^4 + a_6 p + a_7 p\, t^2 + a_8 p\, t^3 + a_9 p\, t^4 + a_{10} p^2 \\ & + a_{11} p^2\, t + a_{12} p^2\, t^2 + a_{13} p^2\, t^3 + a_{14} p^3 + a_{15} p^3\, t + a_{16} p^3\, t^2 \\ & + a_{17}\, p^3\, t^3 + a_{18} p^3\, t^4 \\ & - S\,(b_1 + b_2\, t + b_3\, t^2 + b_4 t^3 + b_5 p + b_6 p^2)\end{aligned}$$

In this equation ρ is the seawater density expressed in kg/m^3, t is the temperature expressed in °C, p is the pressure expressed in MPa and S is the salinity expressed in g/kg. Parameters a and b have the following values:

$a_1 = 9.992 \times 10^{2}$	$a_2 = 9.539 \times 10^{-2}$	$a_3 = -7.619 \times 10^{-3}$	$a_4 = 3.131 \times 10^{-5}$
$a_5 = -6.174 \times 10^{-8}$	$a_6 = 4.337 \times 10^{-1}$	$a_7 = 2.549 \times 10^{-5}$	$a_8 = -2.899 \times 10^{-7}$
$a_9 = 9.578 \times 10^{-10}$	$a_{10} = 1.763 \times 10^{-3}$	$a_{11} = -1.231 \times 10^{-4}$	$a_{12} = 1.366 \times 10^{-6}$
$a_{13} = 4.045 \times 10^{-9}$	$a_{14} = -1.467 \times 10^{-5}$	$a_{15} = 8.839 \times 10^{-7}$	$a_{16} = -1.102 \times 10^{-9}$
$a_{17} = 4.247 \times 10^{-11}$	$a_{18} = -3.959 \times 10^{-14}$	$b_1 = -7.999 \times 10^{-1}$	$b_2 = 2.409 \times 10^{-3}$
$b_3 = -2.581 \times 10^{-5}$	$b_4 = 6.856 \times 10^{-8}$	$b_5 = 6.298 \times 10^{-4}$	$b_6 = -9.363 \times 10^{-7}$

This equation is valid for temperatures between 0°C and 180°C, pressures between 0.1 MPa and 100 MPa, and salinities between 0 g/kg and 80 g/kg. The accuracy of the predicted density is ± 2½ %.

Write a MATLAB program to calculate the density of seawater under the following conditions:

a) t = 22.0°C, p = 0.12 MPa, S = 34.0 g/kg
b) t = 14.0°C, p = 0.25 MPa, S = 35.5 g/kg
c) t = 45.6°C, p = 0.13 MPa, S = 52.3 g/kg

State your answer to four significant figures.