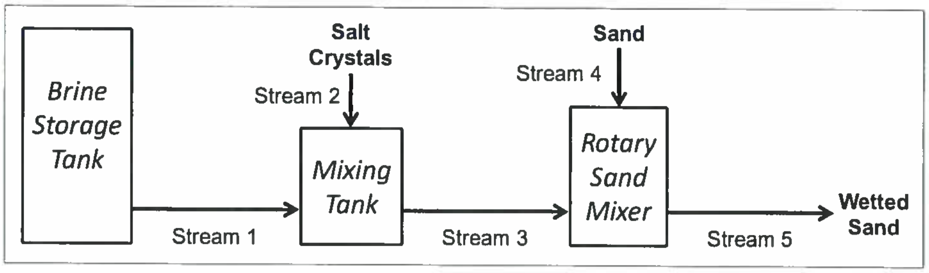
QUESTION 1 (*9 marks*)



In preparation for an impending winter snow storm, the city plow crew is preparing a batch of sand wetted with brine. Brine is the name given to a mixture of NaCl and water. Coating the sand grains with brine allows them to adhere better to the ice layer that often develops at road intersections. The process used to make batches of wetted sand is shown in the figure above.

A 9.7 mass% NaCl solution is kept in a brine storage tank. When making a batch of wetted sand, a certain amount of that NaCl solution is pumped from the brine storage tank to a mixing tank (stream 1) where it is mixed with dry NaCl crystals (stream 2) to create a brine that contains 23.3 mass% NaCl (which is the eutectic composition for brine and has a freezing point of -21.13°C). The entire eutectic mixture is then pumped to a Rotary Sand Mixer (stream 3) where it is mixed with dry sand (stream 4) to produce wetted sand which leaves the mixer in stream 5. The wetted sand contains 5 kg of eutectic brine per 100 kg of dry sand.

Answer the questions below based on the plow crew wanting to manufacture a 3000 kg batch of wetted sand.

3 **(a)** Calculate the mass (in kg) of eutectic brine in the batch of wetted sand.

There is 5 kg of eutectic brine for every 100 kg of sand in the wetted sand

$\therefore$ mass fraction of brine in sand = $\dfrac{5\text{ kg brine}}{5\text{ kg brine} + 100\text{ kg sand}} = 0.0476$

$\therefore$ mass of brine in 3000 kg of wetted sand = $(3000\text{ kg})(0.0476) = \boxed{142.86\text{ kg}}$

1 **(b)** Determine the mass (in kg) of dry sand that needs to be added to the rotary sand mixer via stream 4 to make this batch of wetted sand.

mass of dry sand = 3000 kg wetted sand − 142.86 kg brine

$= \boxed{2857.14\text{ kg}}$

QUESTION 1 ***Contd.***

(c) Calculate the total mass (in kg) of the 9.7 mass% brine that needs to be pumped from the brine storage tank to the mixing tank (stream 1) to make a 3000 kg batch of wetted sand.

4 brine balance around rotary sand mixer

$$\text{brine in stream 3} + \cancel{\text{brine in stream 4}}^{\,0} - \text{brine out stream 5} + \cancel{\text{brine generated}}^{\,0} = \cancel{\text{brine accumulated}}^{\,0}$$

$$\text{brine in stream 3} = \text{brine in stream 5} = 142.86\ kg.$$

water balance around mixing tank

$$\text{water in stream 1} + \cancel{\text{water in stream 2}}^{\,0} - \text{water out stream 3} + \cancel{\text{water generated}}^{\,0} = \cancel{\text{water accumulated}}^{\,0}$$

$$\therefore \text{water in stream 1} = \text{water in stream 3} = (1-0.233)(142.86\ kg) = 109.57\ kg.$$

$$\text{mass of salt in stream 1} = (109.57\ kg)\left(\frac{9.7\ kg\ NaCl}{90.3\ kg\ H_2O}\right) = 11.77\ kg$$

$$\therefore \text{mass of 9.7 mass\% brine in stream 1} = 109.57\ kg + 11.77\ kg = \boxed{121.34\ kg}$$

(d) Determine the mass (in kg) of salt crystals that needs to be added to the mixing tank via stream 2 to make this batch of wetted sand.

1 mass balance around mixing tank.

$$\text{mass in stream 1} + \text{mass in stream 2} = \text{mass out stream 3}$$

$$(121.34\ kg) + \text{mass in stream 2} = 142.86\ kg.$$

$$\therefore \text{mass in stream 2 (salt crystals)} = \boxed{21.52\ kg}$$

QUESTION 2 (*16 Marks*)

The tables below provide experimental P-V-T data for water (M_{H_2O} = 18.02 kg/kmol) in the liquid-vapor region and in a single phase region. Use this data to answer the questions below.

In the Liquid-Vapour Region			
T (°C)	**P (kPa)**	**V_L (m^3/kg)**	**V_V (m^3/kg)**
50	12.350	0.001012	12.0318
100	101.3	0.001044	1.67290
200	1553.8	0.001156	0.12736
300	8581.0	0.001404	0.02167
374.1	22089	0.00315	0.00315

In a Single Phase Region		
T (°C)	**P (kPa)**	**V (m^3/kg)**
200	1000	0.20596
200	5000	0.001153
300	30000	0.001330
400	500	0.61728

(a) Estimate the vapor pressure (in kPa) of water at 250°C.

Assuming a linear increase in vapor pressure with temperature

2 $P_{vap}(250°C) = \dfrac{1553.8 \text{ kPa} + 8581 \text{ kPa}}{2} = \boxed{5067.4 \text{ kPa}}$

(b) What are the critical temperature (in °C) and critical pressure (in kPa)?

1 $T_c = 374.1\ °C$ $\qquad P_c = 22089$ kPa.

(c) 20 grams of water is placed in a variable volume vessel. If the temperature is maintained constant at 200°C, provide the phases present when the vessel volume is changed to the values listed below (*Note: You must show your work to receive full marks*)

(i) Volume of the vessel is 4.00 liters.

mass of water $= (20g)(1 kg/1000g) = 0.02$ kg.

2 volume of water $= (4L)(1 m^3/1000L) = \cancel{4000}\ 0.004 m^3$

$V = \dfrac{\text{volume}}{\text{mass}} = \dfrac{0.004 m^3}{0.02 kg} = 0.2 m^3/kg$.

At 200°C, since $V > V_V$, there is only a $\boxed{\text{VAPOUR}}$

(ii) Volume of the vessel is 2.00 liters.

1 volume of water $= (2L)(1m^3/1000L) = 0.002 m^3$

$V = \dfrac{v}{m} = \dfrac{0.002 m^3}{0.02 kg} = 0.1 m^3/kg$.

At 200°C, since $V_L < V < V_V$, there is a $\boxed{\text{VAPOUR-LIQUID}}$ mixture

QUESTION 2 ***Contd.***

(iii) Volume of the vessel is 23 cm^3.

$v = (23\,cm^3)(1\,m^3/10^6\,cm^3) = 2.3\times10^{-5}\,m^3$

2 $V = \frac{v}{mass} = 2.3\times10^{-5}\,m^3/0.02\,kg = 1.15\times10^{-3}\,m^3/kg$

at 200°C, since $V < V_L$, there is only a $\boxed{\text{LIQUID}}$

(d) A fixed mass of water is contained in a rigid vessel at 300°C. At this temperature, the water exists as a saturated vapor.

(i) What is the pressure (in kPa) in the vessel under these conditions?

1 $P = 8581$ kPa

(ii) If the vessel and contents are allowed to cool to 100°C, calculate the mass fraction of each phase present at equilibrium.

3 L — V

$V_L = 0.001044\,m^3/kg$ $\quad V_{mix} = 0.02167\,m^3/kg$ $\quad V_V = 1.6729\,m^3/kg$

$$\text{mass fraction of liquid} = \frac{V_V - V_{mix}}{V_V - V_L} = \frac{(1.6729 - 0.02167)\,m^3/kg}{(1.6729 - 0.001044)\,m^3/kg} = \boxed{0.988}$$

$\therefore$ mass fraction of vapour $= 1 - 0.988 = \boxed{0.012}$

(iii) If the vessel and contents are heated to 374°C, calculate the mass fraction of each phase present at equilibrium. Calculate the degrees of freedom under these conditions.

3 under these conditions there is only a vapour $\rightarrow P = 1$

$\therefore F = C - P + 2 = 1 - 1 + 2 = \boxed{2}$

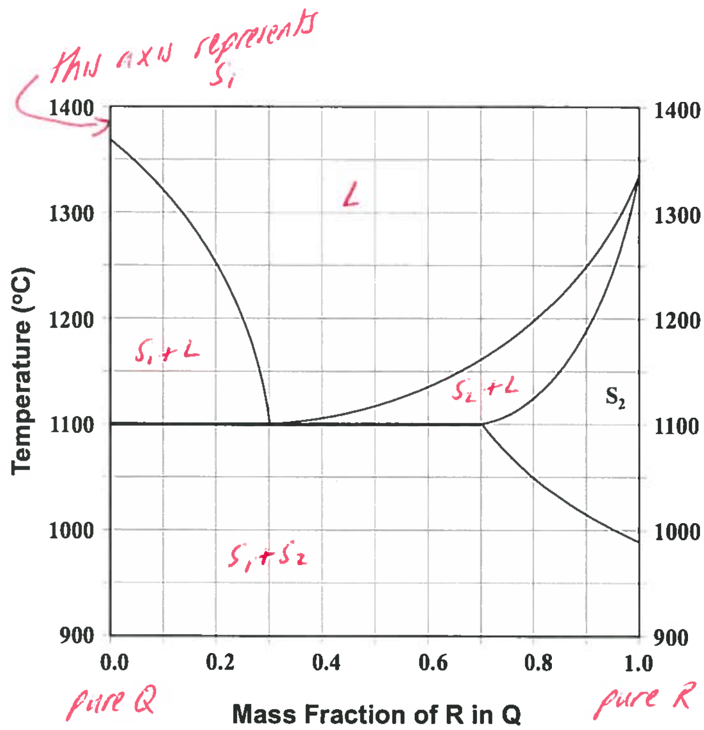
(e) What state would you define water to be in at 300°C and 30000 kPa? Explain why in 20 words or less.

1 Since $T < T_c$, $P > P_c$ and $V < V_c$, it must be a $\boxed{\text{liquid}}$

QUESTION 3 (*21 Marks*)

The phase diagram to the right summarizes solid-liquid equilibrium data for binary mixtures composed of Component Q (M_Q = 70 kg/kmol) and Component R at a constant pressure of 1 atm.

Use the phase diagram provided to answer the following questions (*note: in order to receive full marks, you must show all of your work*).



1 **(a)** On the phase diagram, clearly label each unlabeled region.

1 **(b)** What is the maximum solubility (in mass%) of Q in R?

30 mass % Q in R

(c) A solid 70 kg piece of pure Component Q is placed in a rigid vessel. Next, a solid 30 kg piece of pure Component R is placed in the same vessel. The vessel is then sealed, and heated at a constant pressure of 1 atm.

1 **(i)** During the heating process, what is the minimum temperature (in °C) at which there will only be liquid in the container at equilibrium?

Since you are starting with solid Q and solid R, you will have to raise the temperature to the point where both have melted. This will occur at approximately $\boxed{1370°C}$

(ii) Determine the overall composition (in mass %) of the liquid in the vessel if the temperature is raised to 1390°C.

2

$$\text{mass \% Q} = \frac{70 \text{ kg}}{70\text{kg} + 30\text{kg}} \times 100\% = 70 \text{ mass \%}$$

$$\text{mass \% R} = 100 \text{ mass \%} - 70 \text{ mass \%} = 30 \text{ mass \%}$$

QUESTION 3 ***Contd.***

2 **(iii)** If you are told that there are a total of 1250 mol within the container, determine the molar mass (in kg/kmol) of component R?

$$\frac{\text{mass } Q}{\text{Molar mass } Q} + \frac{\text{mass } R}{\text{Molar mass } R} = \text{Total moles of mixture}$$

$$\frac{70\text{ kg}}{70\text{ kg/kmol}} + \frac{30\text{ kg}}{\text{Molar mass } R} = 1.25\text{ kmol}.$$

$$\therefore \text{ Molar mass } R = \boxed{120\text{ kg/kmol}}$$

2 **(iv)** If the mixture is cooled from a starting temperature of 1390°C, specify the temperature (in °C) at which you would first observe a phase change occurring in the vessel. At this temperature, clearly specify the composition (in mass%) of each of the phases present at equilibrium.

1100°C (Three phase line)

composition: S_1 = 100 mass % Q   0 mass % R
S_2 = 70 mass % R   30 mass % Q
L = 30 mass % R   70 mass % Q

(d) A sample containing 7.5 kg of Component 'R' and 42.5 kg of Component 'Q' is at an equilibrium temperature of 1390°C. More Component R is added isothermally to the mixture, and the resulting mixture is allowed to cool down to 1250°C.

3 **(i)** Determine the minimum amount of Component R (in kg) that would need to be added to the mixture to have S_2 present under equilibrium conditions at this temperature.

Composition of mixture. mass fraction $R = \frac{7.5\text{ kg}}{7.5\text{ kg} + 42.5\text{ kg}} = 0.15$

initial conditions: mass of R = 7.5 kg
mass of Q = 42.5 kg

added: assume you add P kg of component R.

final conditions: mass of R = 7.5 kg + P
mass of Q = 42.5 kg.

Composition = 0.9 mass fraction R.
= 0.1 mass fraction Q

$$\therefore \frac{42.5\text{ kg}}{42.5\text{ kg} + 7.5\text{ kg} + P} = 0.1 \longrightarrow \boxed{P = 375\text{ kg}}$$

QUESTION 3 ***Contd.***

(ii) Specify the composition (in mass %) of the S_2 phase at equilibrium.

1 95 mass % R

(e) A 200 g sample containing 10 mass% component 'R' in component 'Q' is cooled from a temperature of 1385°C to a new equilibrium temperature of 1200°C which results in a solid-liquid mixture at equilibrium.

(i) Determine the composition (in mol %) of the solid phase at 1200°C.

1 Solid S_1 is pure Q (100 mol % Q)

(ii) Determine the mass (in g) of solid present at an equilibrium temperature of 1200°C.

2 S_1 L

$X_{S_1} = 0$ $X_{mix} = 0.1$ $X_L = 0.25$

$$\text{mass solid} = \left(\frac{X_L - X_{mix}}{X_L - X_{S_1}}\right)(M_{TOTAL}) = \left(\frac{0.25 - 0.1}{0.25 - 0}\right)(200\,g) = \boxed{120\,g}$$

(iii) Continuing from part (e)(ii), you drain all the liquid into a second vessel, and allow the contents of the second vessel to cool to an equilibrium temperature of 1150 °C. Calculate the mass (in g) of liquid present at equilibrium.

3 S_1 L

$X_{S_1} = 0$ $X_{mix} = 0.25$ $X_L = 0.28$

$$\frac{M_L}{M_{TOTAL}} = \frac{X_{mix} - X_{S_1}}{X_L - X_{S_1}} \rightarrow M_L = \left(\frac{0.25 - 0}{0.28 - 0}\right)(80\,g) = \boxed{71.43\,g}$$

(f) Calculate the degrees of freedom remaining in any two-phase region in the graph provided.

2 $F = C - P + 2 = 2 - 2 + 2 = 2$

but 1 degree of freedom is used up by fixing pressure

$\therefore \boxed{F = 1}$

Question 4 *(15 Marks)*

Welding is a process in which materials, usually metals, are joined together. The quality of a weld can be negatively affected by the oxygen and water vapour normally found in the air. For this reason, the joint is often blanketed with a shielding gas mixture during the welding process.

You are employed as an engineering intern at a company that makes specialty gas mixtures for many applications including welding. You are given the task of making a gas mixture containing argon (Ar), helium (He) and carbon dioxide (CO_2) that supports the welding of stainless steel to carbon steel. You find the following standard procedure in a company manual to make the requested mixture:

Step 1: Evacuate a rigid 4 m^3 vessel.

Step 2: Add pure CO_2 (M_{CO_2} = 44.01 kg/kmol) until the pressure is 15 kPa.

Step 3: Add pure He (M_{He} = 4.00 kg/kmol) until the pressure is 277.5 kPa.

Step 4: Add 30.98 kg of pure Ar (M_{Ar} = 39.95 kg/kmol) to the vessel.

Assuming the temperature in the container remains constant at 20°C throughout this process, and the gases act in an ideal manner, use the information provided to answer the following questions:

(a) Calculate the molar volume (in m^3/kmol) of CO_2 in the tank after step 2.

1 $$PV_m = RT \rightarrow V_m = \frac{RT}{P} = \frac{\left(8.314 \frac{kPa\,m^3}{kmol\,K}\right)(273.15+20)K}{15\,kPa}$$

$$V_m = \boxed{162.48\ m^3/kmol}$$

(b) Calculate the amount (in kmol) of He in the tank after step 3.

3 $$\text{moles present after step 2} = n_1 = \frac{V}{V_m} = \frac{4m^3}{162.48\,m^3/kmol} = 0.0246\,kmol$$

$$\text{moles present after step 3} = n_2 = \frac{PV}{RT} = \frac{(277.5\,kPa)(4m^3)}{\left(8.314 \frac{kPa\,m^3}{kmol\,K}\right)(293.15K)}$$

$$n_2 = 0.4554\ kmol.$$

$$\therefore \text{amount of helium added} = n_2 - n_1 = 0.4554\,kmol - 0.0246\,kmol$$

$$= \boxed{0.4308\ kmol}$$

Question 4 ***Contd.***

(c) Calculate the pressure (in kPa) of the final mixture after step 4.

2

moles of Ar added $= n_{Ar} = \dfrac{30.98\,kg}{39.95\,kg/kmol} = 0.7755\,kmol$

$\therefore n_3 =$ total moles after Ar added $= n_2 + n_{Ar} = 0.4554\,kmol + 0.7755\,kmol$

$= 1.2309\,kmol$

$\therefore P = \dfrac{n_3 RT}{V} = \dfrac{(1.2309\,kmol)(8.314\,\frac{kPa\,m^3}{kmol\,K})(293.15\,K)}{4\,m^3} = \boxed{750\,kPa}$

(d) What is the partial pressure (in kPa) of He in the final mixture after step 4?

2

$P_{He} = y_{He} P$

$y_{He} = \dfrac{\text{moles He}}{\text{total moles}} = \dfrac{0.4308\,kmol}{1.2309\,kmol} = 0.35$

$\therefore P_{He} = (0.35)(750\,kPa) = \boxed{262.5\,kPa}$

(e) What is the partial volume (in m^3) of He in the final mixture after step 4?

2

$V_{He} = \dfrac{(n_{He})(R)(T)}{P} = \dfrac{(0.4308\,kmol)(8.314\,\frac{kPa\,m^3}{kmol\,K})(293.15\,K)}{750\,kPa}$

$= \boxed{1.4\,m^3}$

(f) What is the average molar mass (in kg/kmol) of the final mixture after step 4?

2

$M_{mix} = y_{CO_2} M_{CO_2} + y_{He} M_{He} + y_{Ar} M_{Ar}$

$y_{CO_2} = \dfrac{0.0246\,kmol}{1.2309\,kmol} = 0.02$

$y_{Ar} = \dfrac{0.7755\,kmol}{1.2309\,kmol} = 0.63$

$M_{mix} = (0.02)(44.01\,kg/kmol) + (0.35)(4\,kg/kmol) + (0.63)(39.95\,kg/kmol)$

$= \boxed{27.45\,kg/kmol}$

Question 4 ***Contd.***

(g) If the gas mixture in the vessel after step 4 was heated from 20°C to 40°C, calculate the change in density (in kg/m³) as a result of this heating process.

1 vessel is rigid → does not change

mass in vessel is constant

$\therefore$ $\boxed{\text{density will not change}}$ $\left(\text{density} = \frac{\text{mass}}{\text{volume}}\right)$

(h) After filling the vessel, a leak develops. Assuming the gas mixture exits the vessel at a constant rate of 17.8 mol/min, how long (in hours) will it take to reach a pressure of 1 atm in the vessel? ↳ 101.325 kPa

2

$$n_{final} = \frac{PV}{RT} = \frac{(101.325\ kPa)(4\ m^3)}{\left(8.314\ \frac{kPa.m^3}{kmol/K}\right)(293.15\ K)}$$

$$= 0.1663\ kmol$$

$\therefore$ moles that have leaked $= 1230.9\ mol - 166.3\ mol$

$$= 1064.6\ mol$$

$\therefore$ time to reach 1atm $= \left(\frac{1064.6\ mol}{17.8\ mol/min}\right)\left(\frac{1\ h}{60\ min}\right)$

$$= \boxed{1\ h}$$