



CHG 2317 (Sep – Dec 2017)
Introduction to the analysis and design of chemical processes

Mid-term Exam – October

Friday October 20, 2017: 14:30 – 15:45 h
Duration: 75 minutes

Lecturer: Marten Ternan
2 pages

Open Book (Felder, Rousseau, and Bullard)
Open class notes, open assignments, open quizzes
Scientific Calculators are permitted.

Student name _____

Back-packs and large purses are to be placed at the front of the examination room
Any communication (the internet or other means) outside the examination room is forbidden

Having a cell phone on one's person is an automatic failure

List any assumptions made in answering a question.

All 5 questions and parts of questions must be answered.

Registration number _____

The number of marks for each question is indicated at the beginning of the question.

1.[8 marks] A gaseous mixture of air and water vapour at 101325 Pa has a temperature of 80°C and a relative humidity of 40%. Then it is cooled from 80 to 15°C at a constant pressure of 101325 Pa.

(a)[3 part marks] Estimate the dew point temperature [°C] of the gaseous mixture and consequently the 'degree of superheat' when the mixture was at 80°C.

(b)[3 part marks] What is the amount of water condensed (in moles) per cubic meter of gas after the temperature of the gas mixture becomes 15°C?

(c)[2 part marks] Alternatively, the initial gaseous mixture at 80°C is placed in a container having a piston. The piston is moved to decrease the container volume and increase its pressure at constant temperature. At what pressure [bar] does the first drop of water appear?

2.[8 marks] Steam is used to provide heat to a reboiler (a heat exchanger). Steam enters the tube side of the reboiler at 190°C at 500 kPa at a flow rate of 1000 kg/h. The steam condenses in the tubes to form condensate (water in the liquid phase) that is also at a pressure of 500 kPa. The condensate leaves the reboiler through a steam trap.

(a)[5 part marks] How much heat [MJ/h] is transferred to the reboiler from the steam?

(b)[0.5 part mark] The steam (a fluid) can be considered as a system. Every thing else would be the environment. Is any work done in the above situation (yes or no)?

(c)[0.5 part mark] If so, does the steam do work on the environment, or does the environment do work on the steam?

(d)[2 part marks] Calculate the amount of work done [MJ/h].

3.[3 marks] Use the compressibility factor equation of state to determine the molar volumes (L/mole) of saturated propane gas and saturated propane liquid at 78°C.

4.[3 marks] A gaseous phase mixture of air and acetone is inside a rigid container. It is at equilibrium with liquid phase acetone at a temperature of 40°C and a pressure of 5000 mmHg. Gaseous mixtures of air and acetone containing between 2.6 and 13% mol acetone are known to burn explosively if they are exposed to a flame or a spark. Determine whether or not there is a risk of an explosion occurring in the gaseous mixture that is inside the rigid container.

5.[3 marks] How much heat (kJ) is required to change the temperature of a mixture of nitrogen (mole fraction = 0.7) and water (mole fraction = 0.3) from 100°C to 500°C at 1 atmosphere.

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1.[8 marks] A gaseous mixture of air and water vapour at 101325 Pa has a temperature of 80°C and a relative humidity of 40%. Then it is cooled from 80 to 15°C at a constant pressure of 101325 Pa.

(a)[3 part marks] Estimate the dew point temperature [°C] of the gaseous mixture and consequently the 'degree of superheat' when the mixture was at 80°C.

(b)[3 part marks] What is the amount of water condensed (in moles) per cubic meter of gas after the temperature of the gas mixture becomes 15°C?

(c)[2 part marks] Alternatively, the initial gaseous mixture at 80°C is placed in a container having a piston. The piston is moved to decrease the container volume and increase its pressure at constant temperature. At what pressure [bar] does the first drop of water appear?

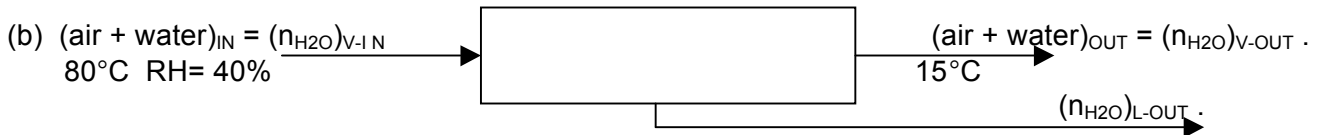
Basis of calculation=1 m³ of gas at 80°C,40% RH,101.325 kPa—see 1(b) [1 mark for any basis of calculation]

(a) Saturated vapour pressure water at 80°C (P^{SAT}_{80}) = 0.4736 bar = 47.36 kPa = 47360 Pa Table B5 page 642
(47360 Pa * 760 mmHg) / 101325 Pa = 355.2 mmHg Table B.3 page 639

40% Relative humidity = 0.4 * 47360 Pa = 18944 Pa = 0.18944 bar approx 59°C Table B6 page 644

Dew point temperature = 59°C [1 mark] (18944 Pa * 760 mmHg) / 101325 Pa = 142.1 mmHg

Degrees of superheat = 80 – 59 = 21 degrees of superheat [1 mark]



at 80°C $T = 273 + 80 = 353 \text{ K}$ mol fract H_2O in = $(y_{\text{H}_2\text{O}})_{\text{IN}} = \frac{0.18944}{1.01325} = 0.1870$ [0.5 mark]

Total gas in = $(n_{\text{T-GAS}})_{\text{IN-80}} = \frac{PV}{RT} = \frac{101325 \text{ Pa} * \frac{N}{\text{m}^2 \text{ Pa}} * 1 \text{ m}^3}{\frac{8.301 \frac{\text{J}}{\text{mol K}} * 353 \text{ K}}$ = 34.579 total moles [0.5 mark]

$(n_{\text{H}_2\text{O}})_{\text{V-IN}} = 34.579 * 0.1870 = 6.466$ moles H_2O [0.5 mark]

34.579 total moles – 6.466 moles $\text{H}_2\text{O} = 28.113$ moles dry air $\text{IN}_{\text{DRY-AIR}} = \text{OUT}_{\text{DRY-AIR}}$

Saturated vapour pressure of water at 14°C, $(P^{\text{SAT}})_{14} = 0.01597 \text{ bar} \rightarrow$ at 16°C, $(P^{\text{SAT}})_{16} = 0.01817$
Table B5 page 642

$(P^{\text{SAT}})_{15} = (P^{\text{SAT}})_{14} + 0.5 [(P^{\text{SAT}})_{16} - (P^{\text{SAT}})_{14}]$ [0.5 mark for any interpolation]
0.00220

at 15°C $(P^{\text{SAT}})_{15} = 0.01597 + 0.5 * (0.01817 - 0.01597) = 0.01597 + 0.00110 = 0.01707 \text{ bar}$

at 15°C $T = 273 + 15 = 288 \text{ K}$ $(y_{\text{H}_2\text{O}})_{\text{OUT}} = \frac{0.01707}{1.01325} = 0.016848$ $(y_{\text{DRY-AIR}}) = 1 - 0.016848 = 0.9832$

$(n_{\text{T-GAS}})_{\text{OUT-15}} = \frac{28.113 \text{ moles dry air}}{0.9832 \text{ mols dry air / total mol}} = 28.594$ total moles out

$(n_{\text{H}_2\text{O}})_{\text{V-OUT}} = 28.594 \text{ total moles out} * [(y_{\text{H}_2\text{O}})_{\text{OUT}} = 0.016848] = 0.4818$ moles H_2O [0.5 mark]

Condensed $\text{H}_2\text{O} = (n_{\text{H}_2\text{O}})_{\text{L-OUT}} = 6.466 - 0.4818 = 5.984$ moles H_2O per m³ [0.5 mark]

(c) It will condense when the H₂O partial pressure = saturation vapour pressure at 80°C

$$p_{\text{H}_2\text{O}} = y_{\text{H}_2\text{O}} P = (P^{\text{SAT}})_{80} \quad [1 \text{ mark}]$$

$$p_{\text{H}_2\text{O}} = 0.187 * P = 0.4736 \text{ bar} \quad P = 2.533 \text{ bar} \quad [1 \text{ mark}]$$

2. [8 marks] Steam is used to provide heat to a reboiler (a heat exchanger). Steam enters the tube side of the reboiler at 190°C at 500 kPa at a flow rate of 1000 kg/h. The steam condenses in the tubes to form condensate (water in the liquid phase) that is also at a pressure of 500 kPa. The condensate leaves the reboiler through a steam trap.

(a)[5 part marks] How much heat [MJ/h] is transferred to the reboiler from the steam?

(b)[0.5 part mark] The steam (a fluid) can be considered as a system. Every thing else would be the environment. Is any work done in the above situation (yes or no)?

(c)[0.5 part mark] If so, does the steam do work on the environment, or does the environment do work on the steam?

(d)[2 part marks] Calculate the amount of work done [kJ/h].

Basis of calculation = 1000 kg/h steam [1 mark for any basis of calculation]

$$500 \text{ kPa} * \frac{1 \text{ bar}}{100 \text{ kPa}} = 5 \text{ bar}$$

Interpolate steam table data between superheated steam at 200°C and 151.8°C saturated steam

$$\frac{190 - 151.8}{200 - 151.8} = \frac{H-190 - 2747.5}{2855 - 2747.5} = \frac{V-190 - 0.375}{0.425 - 0.375} \quad [1 \text{ mark for any interpolation}]$$

$$\frac{190 - 151.8}{200 - 151.8} = \frac{H-190 - 2747.5}{107.5} = \frac{V-190 - 0.375}{0.05}$$

$$\frac{190 - 151.8}{200 - 151.8} = \frac{38.2}{48.2} = 0.7925$$

$$H-190 = 2747.5 + 0.7925 * 107.5 = 2833 \frac{\text{kJ}}{\text{kg}} = \text{Enthalpy of steam entering reboiler tubes} \quad [1 \text{ mark}]$$

$$V-190 = 0.375 + 0.7925 * 0.05 = 0.415 \frac{\text{m}^3}{\text{kg}} = \text{Volume of steam entering reboiler tubes}$$

$$640.1 \frac{\text{kJ}}{\text{kg}} = \text{Enthalpy of saturated water (condensate) about to leave reboiler tubes, prior to entering steam trap} \quad [1 \text{ mark}]$$

$$0.00109 \frac{\text{m}^3}{\text{kg}} = \text{Volume of saturated water (condensate) about to leave reboiler tubes, prior to entering steam trap}$$

HEAT transferred = enthalpy change at constant pressure

$$\text{HEAT transfer in reboiler} = 1000 \frac{\text{kg}}{\text{h}} * (2833 \frac{\text{kJ}}{\text{kg}} - 640 \frac{\text{kJ}}{\text{kg}}) = 2193 \frac{\text{MJ}}{\text{h}} \quad [1 \text{ mark}]$$

$$\text{WORK} = -\int P dV = -P (V_{\text{OUT}} - V_{\text{IN}}) \quad [1 \text{ mark for formula}]$$

$$= -500 \text{ kPa} * (0.00109 - 0.415) \frac{\text{m}^3}{\text{kg}} * 1000 \frac{\text{kg}}{\text{h}} * \frac{\text{N}}{\text{Pa m}^2} * \frac{\text{J}}{\text{N m}} = +207 \frac{\text{MJ}}{\text{h}}$$

[1 mark for correct numerical answer]

Work is performed [0.5 mark]

Work is done on the fluid (on steam = on the system) [0.5 mark]

3. [3 marks] Use the compressibility factor equation of state to determine the molar volumes (L/mole) of saturated propane gas and saturated propane liquid at 78°C and 3.192 MPa.

$$T = 78^\circ\text{C} \quad 78 + 273.2 = 351.2 \text{ K} \quad T_c = 369.9 \text{ K} \quad T_r = T / T_c = 351.2 / 369.9 = 0.949$$

0.5 mark for the correct critical temperature

Fig 5.4-1 Felder Rousseau Bullard $z(\text{gas}) = 0.59$ Intersection of T_r and saturated gas line = $P_r = 0.75$
 $z(\text{liquid}) = 0.1$ from intersection of $P_r = 0.75$ and saturated liquid line
 0.5 mark if at least one the "z" values is correct

$$P_c = 42 \text{ atm} \quad P = P_r * P_c = 0.75 * 42 \text{ atm} = 31.5 \text{ atm} * 101.3 \text{ kPa /atm} = 3192 \text{ kPa} = 3.192 \text{ MPa}$$

0.5 mark for the correct pressure

$$V_{\text{GAS}} = \frac{z RT}{P} \leftarrow 1 \text{ mark for the correct formula for the compressibility factor equation of state}$$

$$V_{\text{GAS}} = \frac{z RT}{P} = \frac{0.59 * 8.314 \text{ J} * \frac{\text{N m}}{\text{mole K}} * 351.2 \text{ K}}{3,192,000 \text{ Pa} * \frac{\text{N}}{\text{m}^2 \text{ Pa}}} = 0.540 * 10^{-3} \frac{\text{m}^3}{\text{mole}} * 10^3 \frac{\text{L}}{\text{m}^3} = 0.540 \frac{\text{L}}{\text{mole}}$$

$$V_{\text{LIQUID}} = \frac{z_{\text{GAS}} RT}{P} * \frac{z_{\text{LIQUID}}}{z_{\text{GAS}}} = 0.540 \frac{\text{L}}{\text{mole}} * \frac{0.1}{0.59} = 0.0915 \frac{\text{L}}{\text{mole}}$$

0.5 mark if one of the "V" values is correct

~~$$T_c = 369.9 \text{ K} \quad P_c = 42 \text{ atm} \quad T = T_r * T_c = 0.95 * 369.9 = 351.4 = 78.2 \text{ C}$$~~
~~$$P = P_r * 42 = 0.75 * 42 = 31.5 \text{ atm} = 3191.7 \text{ kPa}$$~~

4.[3 marks] A gaseous phase mixture of air and acetone is inside a rigid container. It is at equilibrium with liquid phase acetone at a temperature of 40°C and a pressure of 5000 mmHg. Gaseous mixtures of air and acetone containing between 2.6 and 13% mol acetone are known to burn explosively if they are exposed to a flame or a spark. Determine whether or not there is a risk of an explosion occurring in the gaseous mixture that is inside the rigid container.

$$F = C + \pi - 2 = 2 + 2 - 2 = 2 \quad \text{Specify } T = 40^\circ\text{C} \text{ and } P = 5000 \text{ mmHg}$$

Antoine Equation p. 246 – empirical equation

$$\log_{10} P^{\text{SAT}} = A - \frac{B}{T + C} \quad T \text{ }^\circ\text{C}, P \text{ mmHg} \quad A, B, C = \text{constants page 640, Table B-4}$$

[1 mark for correct Antoine equation]

$$\log_{10} P^{\text{SAT}} = 7.11714 - \frac{1210.595}{40 + 229.664} \quad \text{Eq 6.1-4 } A=7.11714 \quad B=1210.595 \quad C=229.664$$

[1 mark for correct constants]

$$\log_{10} P^{\text{SAT}} = 7.1174 - 4.48927 = 2.62783$$

$$P^{\text{SAT}} = 424.5 \text{ mmHg} \quad [0.5 \text{ mark}]$$

$$Y_{\text{ACETONE}} = \frac{424.5}{5000} = 0.085 = 8.5 \% \text{ acetone in vapour mixture} = \text{risk of explosion} \quad [0.5 \text{ mark}]$$

5. [3 marks] How much heat (kJ) is required to change the temperature of a mixture of nitrogen (mole fraction = 0.7) and water (mole fraction = 0.3) from 100°C to 500°C at 1 atmosphere.

Table B.8 Felder Rousseau and Bullard

Basis of calculation = 1 mole of gas mixture ← 1 mark for any basis of calculation

At constant pressure $Q = \Delta H = \text{mole fraction} * [H(500^\circ\text{C}) - H(100^\circ\text{C})] = \Delta H_{\text{COMPONENT}} =$
1 mark for the above formula

Component	mole fraction	H(500°C) kJ/mol	H(100°C) kJ/mol	$\Delta H_{\text{COMPONENT}}$ kJ/mol
N ₂	0.7	14.24	2.19	8.43
H ₂ O	0.3	17.01	2.54	4.34
Total				12.77

Heat required = 12.77 kJ/mole of N₂-H₂O mixture ← 1 mark for the correct answer.