04-CHEM-A1, PROCESS BALANCES and CHEMICAL THERMODYNAMICS

MAY 2016

Three Hours Duration

NOTES:

1) If doubt exists as to the interpretation of any question, you are urged to submit a clear statement of any assumptions made along with the answer paper.

2) Property data required to solve a given problem are provided in the problem statement or are available in the recommended texts. If you are unable to locate the required data, do not let this prevent you from solving the rest of the problem. Even in the absence of property data, you still have the opportunity to provide a solution methodology.

3) This is an open-book exam.

4) Any non-communicating calculator is permitted.

5) The examination is in two parts – Part A (Questions 1 to 3): Process Balances

   Part B (Questions 4 and 6): Chemical Thermodynamics

6) Answer **TWO** questions from Part A and **TWO** questions from Part B.

7) **FOUR** questions constitute a complete paper.

8) Each question is of equal value.

PART A: PROCESS MASS and ENERGY BALANCES

1) Consider an iron blast furnace charged with iron ore, limestone ($CaCO_3$) and coke. The weight analyses of the charge is as follows:

	Fe_2O_3	SiO_2	MnO	Al_2O_3	H_2O	C	$CaCO_3$
Ore	80%	12%	1%	3%	4%		
Limestone		4%			1%		95%
Coke		10%				90%	

The ultimate weight analysis of the pig iron gives 93.8% Fe, 4% C, 1.2% Si and 1% Mn. For every ton of pig iron produced, 1750 kg of iron ore and 500 kg of limestone are used and 4200 m^3 of flue gas is produced. The rational analysis of flue gases gives 58% N_2, 26% CO, 12% CO_2, and 4% H_2O. The reactions occurring in the blast furnace are:

$$Fe_2O_3 + 3CO \leftrightarrow 2Fe + 3CO_2$$

$$CaCO_3 \leftrightarrow CaO + CO_2$$

$$C + ½\, O_2 \leftrightarrow CO$$

$$SiO_2 + 2C \leftrightarrow Si + 2CO$$

$$MnO + C \leftrightarrow Mn + CO_2$$

$$CO_2 + C \leftrightarrow 2CO$$

Determine the following:

a) Quantity of coke used per ton of pig iron
b) Consumption of air per ton of pig iron
c) Composition of the slag

2) Consider the oxidation of toluene given by the following reaction

$$C_6H_5CH_3\ (g) + O_2\ (g) \rightarrow C_6H_5CHO\ (g) + H_2O\ (g)$$

Calculate the standard heat of reaction for oxidation of toluene.

DATA:
Gross heat of combustion of liquid benzaldehyde at 18 °C = – 841.3 kcal/gmol
Normal boiling point of benzaldehyde = 179 °C
Heat of vaporization of benzaldehyde at 179 °C = 86.48 cal/g
Specific heat capacity of liquid benzaldehyde = 0.428 cal/g °C
Specific heat capacity of benzaldehyde vapor = 31 cal/gmol °C
Average molar heat capacity of liquid H_2O = 18 cal/gmol °C
Average molar heat capacity of CO_2 = 8.87 cal/gmol °C
Average molar heat capacity of O_2 = 7.0 cal/gmol °C
Standard heat of formation of H_2O vapor = – 57.8 kcal/gmol
Standard heat of formation of toluene vapor = 11.95 kcal/gmol

3) 1000 kg/hr of a liquid solution of 60 wt% naphthalene ($C_{10}H_8$) and 40 wt% benzene (C_6H_6) at 80 °C is cooled to 10 °C. The resulting solid and liquid phases are separated in a rotary drum filter. The process operates at steady state. Your job is to determine how well the drum filter is performing. You determine that the filtrate liquid flow rate is 505 kg/hr.

(a) How much entrainment (kg entrained/kg solids) does the filter leave?
(b) By how much does any entrainment change the recovery of naphthalene in the filter cake product or the purity of the products?

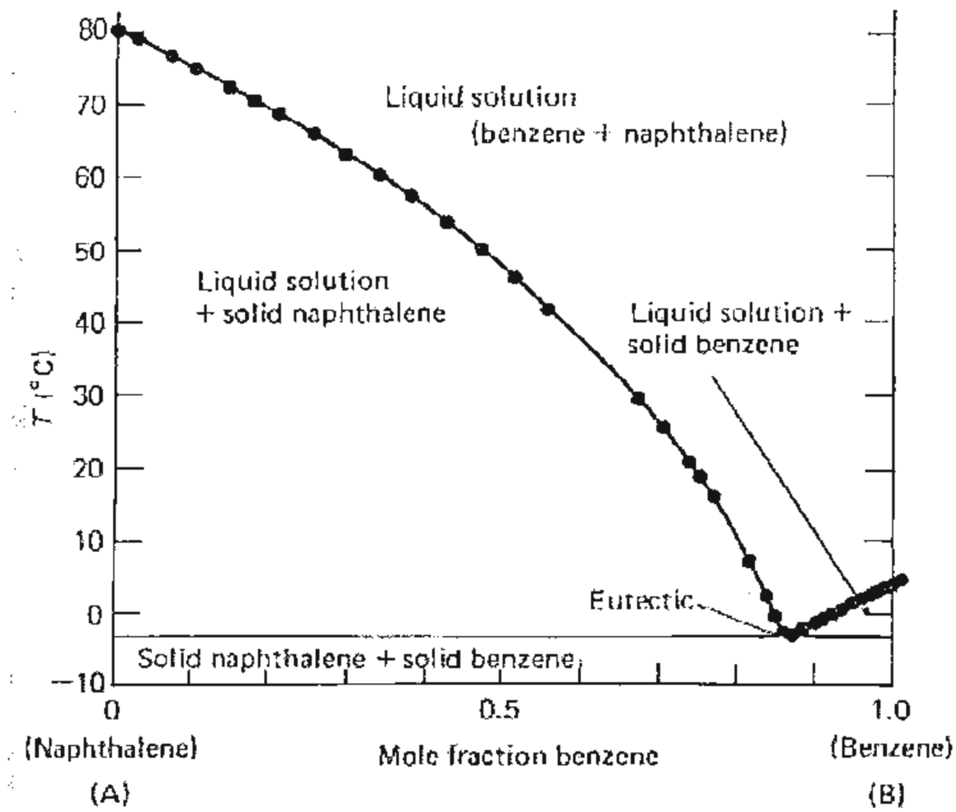

Figure: Liquid-Solid Phase Equilibrium Diagram for Benzene-Naphthalene Mixtures (taken from *"Phase Equilibria in Chemical Engineering"* by Stanley M. Walas, Butterworth Publishers, 1985)

PART B: CHEMICAL THERMODYNAMICS

4) The calcination of sodium bicarbonate takes place according to the following equation:

$$2NaHCO_3\,(s) \leftrightarrow Na_2CO_3\,(s) + CO_2\,(g) + H_2O\,(g)$$

When this reaction was run in the laboratory by placing sodium bicarbonate in an initially evacuated cylinder, it was observed that the equilibrium total pressure was 0.826 kPa at 30 °C and 166.97 kPa at 110 °C. The heat of reaction for the calcination can be assumed to be independent of temperature.

(a) What is the heat of reaction for this reaction?
(h) Develop an equation for the equilibrium constant as a function of temperature.
(c) At what temperature will the partial pressure of carbon dioxide in the reaction vessel be 1 bar?

5) At 45 °C and 40.25 kPa total pressure, a vapor phase containing 43.4 mol% ethanol and 56.6 mol% benzene is in equilibrium with a liquid phase containing 61.1 mol% benzene. The system forms an azeotrope at 45 °C. Assuming that few molecular interactions exist, determine the composition of the azeotrope and the total pressure of the azeotropic system.

DATA: Vapor pressure of pure ethanol at 45 °C = 22.9 kPa
Vapor pressure of pure ethanol at 45 °C = 29.6 kPa

6) A chemical species A is known to decompose according to the following equation:

$$A\ (g) \leftrightarrow B\ (g) + C\ (g)$$

A rigid container is filled with pure gaseous A at 300 K and 760 mmHg, and then heated. The pressure was observed to be 1114 mmHg at 400 K and 1584 mmHg at 500 K. Assuming ideal gas behavior and chemical equilibrium, estimate the pressure for a temperature of 600 K.

The Periodic Table of the Elements

Alkali metals
Alkaline earth metals
Transition metals
Other metals
Metalloids (semi-metal)
Nonmetals
Halogens
Noble gases

Element name → Mercury
80 ← Atomic #
Symbol → Hg
200.59 ← Avg. Mass

1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Hydrogen 1 H 1.01																		Helium 2 He 4.00
Lithium 3 Li 6.94	Beryllium 4 Be 9.01												Boron 5 B 10.81	Carbon 6 C 12.01	Nitrogen 7 N 14.01	Oxygen 8 O 16.00	Fluorine 9 F 19.00	Neon 10 Ne 20.18
Sodium 11 Na 22.99	Magnesium 12 Mg 24.31												Aluminum 13 Al 26.98	Silicon 14 Si 28.09	Phosphorus 15 P 30.97	Sulfur 16 S 32.07	Chlorine 17 Cl 35.45	Argon 18 Ar 39.95
Potassium 19 K 39.10	Calcium 20 Ca 40.08		Scandium 21 Sc 44.96	Titanium 22 Ti 47.88	Vanadium 23 V 50.94	Chromium 24 Cr 52.00	Manganese 25 Mn 54.94	Iron 26 Fe 55.85	Cobalt 27 Co 58.93	Nickel 28 Ni 58.69	Copper 29 Cu 63.55	Zinc 30 Zn 65.39	Gallium 31 Ga 69.72	Germanium 32 Ge 72.61	Arsenic 33 As 74.92	Selenium 34 Se 78.96	Bromine 35 Br 79.90	Krypton 36 Kr 83.80
Rubidium 37 Rb 85.47	Strontium 38 Sr 87.62		Yttrium 39 Y 88.91	Zirconium 40 Zr 91.22	Niobium 41 Nb 92.91	Molybdenum 42 Mo 95.94	Technetium 43 Tc (98)	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.91	Palladium 46 Pd 106.42	Silver 47 Ag 107.87	Cadmium 48 Cd 112.41	Indium 49 In 114.82	Tin 50 Sn 118.71	Antimony 51 Sb 121.76	Tellurium 52 Te 127.60	Iodine 53 I 126.90	Xenon 54 Xe 131.29
Cesium 55 Cs 132.91	Barium 56 Ba 137.33	57-70 *	Lutetium 71 Lu 174.97	Hafnium 72 Hf 178.49	Tantalum 73 Ta 180.95	Tungsten 74 W 183.84	Rhenium 75 Re 186.21	Osmium 76 Os 190.23	Iridium 77 Ir 192.22	Platinum 78 Pt 195.08	Gold 79 Au 196.97	Mercury 80 Hg 200.59	Thallium 81 Tl 204.38	Lead 82 Pb 207.20	Bismuth 83 Bi 208.98	Polonium 84 Po (209)	Astatine 85 At (210)	Radon 86 Rn (222)
Francium 87 Fr (223)	Radium 88 Ra (226)	89-102 **	Lawrencium 103 Lr (262)	Rutherfordium 104 Rf (267)	Dubnium 105 Db (268)	Seaborgium 106 Sg (271)	Bohrium 107 Bh (272)	Hassium 108 Hs (270)	Meitnerium 109 Mt (276)	Darmstadtium 110 Ds (281)	Roentgenium 111 Rg (280)	Copernicium 112 Cn (285)	Ununtrium 113 Uut (284)	Ununquadium 114 Uuq (289)	Ununpentium 115 Uup (288)	Ununhexium 116 Uuh (293)	Ununseptium 117 Uus (294?)	Ununoctium 118 Uuo (294)

*lanthanides	Lanthanum 57 La 138.91	Cerium 58 Ce 140.12	Praseodymium 59 Pr 140.91	Neodymium 60 Nd 144.24	Promethium 61 Pm (145)	Samarium 62 Sm 150.36	Europium 63 Eu 151.97	Gadolinium 64 Gd 157.25	Terbium 65 Tb 158.93	Dysprosium 66 Dy 162.50	Holmium 67 Ho 164.93	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.04
**actinides	Actinium 89 Ac (227)	Thorium 90 Th 232.04	Protactinium 91 Pa 231.04	Uranium 92 U 238.03	Neptunium 93 Np (237)	Plutonium 94 Pu (244)	Americium 95 Am (243)	Curium 96 Cm (247)	Berkelium 97 Bk (247)	Californium 98 Cf (251)	Einsteinium 99 Es (252)	Fermium 100 Fm (257)	Mendelevium 101 Md (258)	Nobelium 102 No (259)