16-CHEM-A1, PROCESS BALANCES and CHEMICAL THERMODYNAMICS

MAY 2019

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. Any non-communicating calculator is permitted.

4) The examination is in two parts – Part A (Questions 1 to 3): Process Balances
   Part B (Questions 4 and 6): Chemical Thermodynamics

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

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

7) Each question is of equal value.

PART A: PROCESS MASS and ENERGY BALANCES

1) An air-conditioning plant is used to maintain a dry-bulb temperature of 27 °C and relative humidity of 50% in an auditorium. The air flow rate to the auditorium is 20,900 m^3/hr at a dry-bulb temperature of 17 °C and relative humidity of 83.5%. The effluent air from the auditorium is partially recycled and mixed with the incoming fresh air, which is fed at a rate of 4,500 m^3/hr at a dry-bulb temperature of 35 °C and relative humidity of 70%. The mixed air, which has a dry-bulb temperature of 29.5 °C and relative humidity of 54%, is passed through the air-conditioning plant to make it suitable for feeding to the auditorium. The total pressure can be assumed to be constant at 1 atm (101.325 kPa).

(a) [11 points] Calculate the moisture removed in the air-conditioning plant.

(b) [3 points] Calculate the moisture added in the auditorium.

(c) [11 points] Calculate the recycle ratio (moles of air recycled per mole of input fresh air)

DATA:

Absolute molar humidity of fresh air at 35 °C = 4.05×10^{-2} moles per mole of dry air

Absolute molar humidity of mixed air at 29.5 °C = 2.25×10^{-2} moles per mole of dry air

Absolute molar humidity of air entering the auditorium at 17 °C = 1.63×10^{-2} moles per mole of dry air

Absolute molar humidity of air leaving the auditorium at 27 °C = 1.81×10^{-2} moles per mole of dry air

2) A mixture containing 75% iron pyrite (FeS_2) ore and 25% zinc sulfide (ZnS) ore by weight are burnt in burner. The pyrites yield 92% FeS_2 and the rest is gangue. The zinc sulfide ore contains 68% ZnS and the rest are inerts. A sample of the cinder product yields 3.5% sulfur with 70% of the sulfur in the cinder in the form of SO_3 absorbed in it and the rest is unoxidized FeS_2. The stochiometrically unbalanced reactions in the burner are as follows:

$$FeS_2 + O_2 \rightarrow Fe_2O_3 + SO_2$$

$$FeS_2 + O_2 \rightarrow Fe_2O_3 + SO_3$$

$$ZnS + O_2 \rightarrow ZnO + SO_2$$

(a) [20 points] Calculate the amount of cinder product formed and its composition based on 100 kg of mixed charge to the burner.

(b) [5 points] Calculate the percentage of sulfur left in the cinder product based on the total sulfur charged.

3) A sulfur burner in a sulfite pump mill burns 200 kg of pure sulfur per hour. The gas leaves the burner at 871 °C and they are cooled before being sent to an absorption tower. As a primary cooler, a waste heat boiler is employed for producing saturated steam at a pressure of 15 bars (absolute). The feed water to the boiler is available at 183 °C and the temperature of the gas mixture leave the boiler is 190 °C. Calculate the amount of steam produced in kg per hour assuming 10% excess air, 90% efficiency, complete combustion, no heat loss to the surroundings and no SO_3 formation.

<u>DATA</u>:

Standard molar specific heat capacity of SO_2 in kJ/kmol.K = $24.7706 + 62.9841 \times 10^{-3}\ T - 4.42582 \times 10^{-5}\ T^2 + 11.122 \times 10^{-9}\ T^3$

Standard molar specific heat capacity of O_2 in kJ/kmol.K = $26.0257 + 11.7551 \times 10^{-3}\ T - 2.3426 \times 10^{-6}\ T^2 - 56.23 \times 10^{-11}\ T^3$

Standard molar specific heat capacity of N_2 in kJ/kmol.K = $29.5909 + 51.141 \times 10^{-4}\ T - 1.31829 \times 10^{-5}\ T^2 - 49.68 \times 10^{-10}\ T^3$

Saturation temperature of steam at 15 bars pressure = 198 °C

Latent heat of vaporization of water at 15 bars pressure = 1945 kJ/kg

Specific heat capacity of water = 4.1868 kJ/kg.K

PART B: CHEMICAL THERMODYNAMICS

1) Water gas, available at a temperature of 500 °C and a pressure 4 bar, has the following composition: 70.4 grams of hydrogen, 23.68 grams of methane, 35.84 grams of ethylene, 66 grams of carbon dioxide, 94.92 grams of carbon monoxide and 50.4 grams of nitrogen.

(a) [5 points] Calculate the volume of water gas if it behaves as an ideal gas.

(b) [20 points] Calculate the volume of water gas if it follows van der Waals equation of state.

DATA:

Component	Formula	Critical Temperature (K)	Critical Pressure (bar)
Hydrogen	H_2	32.2	12.97
Methane	CH_4	190.56	45.99
Ethylene	C_2H_4	282.34	50.41
Carbon Monoxide	CO	132.91	34.99
Carbon Dioxide	CO_2	304.1	73.75
Nitrogen	N_2	126.9	33.94

2) Pyrites are roasted in a roaster plant for making sulfuric acid. The gases leave the roaster at 502 °C with the mass composition: 3.57% SO_2, 1.08% O_2, 0.18% SO_3 and the rest N_2. Calculate the heat content of 1 kmol of gas mixture over 25 °C.

DATA:

Standard molar specific heat capacity of SO_2 in kJ/kmol.K = $24.7706 + 62.9841 \times 10^{-3} T - 4.42582 \times 10^{-5} T^2 + 11.122 \times 10^{-9} T^3$

Standard molar specific heat capacity of O_2 in kJ/kmol.K = $26.0257 + 11.7551 \times 10^{-3} T - 2.3426 \times 10^{-6} T^2 - 56.23 \times 10^{-11} T^3$

Standard molar specific heat capacity of SO_3 in kJ/kmol.K = $22.0376 + 12.1624 \times 10^{-2} T - 9.18673 \times 10^{-5} T^2 - 24.3691 \times 10^{-9} T^3$

Standard molar specific heat capacity of N_2 in kJ/kmol.K = $29.5909 + 51.141 \times 10^{-4} T - 1.31829 \times 10^{-5} T^2 - 49.68 \times 10^{-10} T^3$

3) 2 moles of methane (CH_4) and 3 moles of water react and gaseous mixture containing CH_4, H_2O, CO, CO_2 and H_2 is obtained. Calculate the equilibrium composition of the mixture at 1000 K and 1 atmosphere.

DATA:

Standard Gibbs free energy of formation of CH_4 at 1000 K = 19.3 kJ/mole

Standard Gibbs free energy of formation of H_2O at 1000 K = - 192.72 kJ/mole

Standard Gibbs free energy of formation of CO at 1000 K = - 200.715 kJ/mole

Standard Gibbs free energy of formation of CO_2 at 1000 K = - 396.11 kJ/mole

Standard Gibbs free energy of formation of H_2 at 1000 K = 0 kJ/mole

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)