16-CHEM-A3, HEAT and MASS TRANSFER

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**. One textbook of your choice with notations listed on the margins etc., but no loose notes are permitted into the exam. Candidates may use any **non-communicating** calculator.

4) All problems are worth **25 points**. At least **two problems** from **each part** must be attempted.

5) **Only the first two** questions as they appear in the answer book from each section will be marked.

PART A – HEAT TRANSFER

1) (a) **[15 points]** The inside and outside surface of a hollow sphere at $r = r_1$ and $r = r_2$ ($r_1 < r < r_2$) are maintained at temperatures T_1 and T_2. The thermal conductivity (k) varies with temperatures as $k = k_0 (1 + aT + bT^2)$, where k_0, a and b are constants. Derive an expression for heat flow Q through the sphere.

(b) **[10 points]** A plane wall with isothermal faces T_1 at $x = 0$ and T_2 at $x > 0$ has thermal conductivity (k) that varies with temperature given by expression $k = k_0 (1 + aT)$, where k_0 and a are constants. Derive an expression for heat flow Q through the wall.

2) Ethylene glycol flowing through the inner pipe of a double pipe heat exchanger at a rate of 5500 kg/hr is cooled from 85 °C to 68 °C using toluene as a cooling medium, which enters at 30 °C and leaves at 62 °C. Find the total length of the double pipe heat exchanger required to perform the task in (a) countercurrent operation and (b) cocurrent operation.

DATA:
Thermal conductivity of the metal pipe = 46.52 W/m.K
Thickness of both pipes = 3 mm
Outer diameter of outer pipe = 70 mm
Outer diameter of inner pipe = 43 mm
Thermal conductivity of water = 0.63 $W/m^2.K$

Property	Ethylene Glycol	Toluene
Density (kg/m^3)	1080	840
Specific Heat (kJ/kg.K)	2.68	1.8
Thermal Conductivity(W/m.K)	0.248	0.146
Viscosity (Pa.s)	3.4×10^{-3}	4.4×10^{-4}

3) A solution flowing at a rate of 30,000 kg/hr and containing 10% solids is to be concentrated to 50% solids in an evaporator. Steam is available at a pressure of 202.65 kPa (saturation temperature is 120 °C). The evaporator is working at reduced pressure such that the boiling point is 50 °C. The overall heat transfer coefficient is 2.9 kW/m^2.K. Estimate the economy of steam and the area of heat transfer for (a) feed introduced at 20 °C and (b) feed introduced at 35 °C.

DATA:
Specific heat capacity of feed = 3.98 kJ/kg.K
Latent heat of condensing steam at 202.65 kPa = 2202 kJ/kg
Latent heat of vaporization of water 50 °C = 2383 kJ/kg

PART B – MASS TRANSFER

1) Acetic acid (CH_3COOH) diffuses across a 1-mm thick film of non-diffusing water. The concentration of acetic acid on opposite sides of water film are 9% by weight (density = 1012 kg/m^3) and 4% by weight (density = 1003.2 kg/m^3). Calculate the rate of diffusion of acetic acid at 17 °C.

DATA: The diffusivity of acetic acid in water at 25 °C = 1.11 x 10^{-9} m^2/s
Viscosity of acetic acid solution at 25 °C = 1.1336 x 10^{-3} Pa.
Viscosity of acetic acid solution at 17 °C = 1.2883 x 10^{-3} Pa.s

2) The equilibrium data for distribution of SO_2 gas between air and water in the dilute concentration region can be approximated by the equation $P_A = 25\ X_A$, where P_A is the partial pressure of SO_2 in the vapor in atmospheres and X_A is the mole fraction of SO_2 in the liquid. For an absorption column operating at 10 atm pressure, the mole fraction of SO_2 in vapor and liquid at one point in the column are Y_A = 0.04 and X_A = 0.01, respectively. The individual mass transfer coefficients in vapor and liquid are:

$$k'_y = 10 \text{ kmol per m}^2 \text{ per hour per mole fraction}$$

$$k'_x = 8 \text{ kmol per m}^2 \text{ per hour per mole fraction}$$

Assuming the transfer of SO_2 through a stagnant film, determine the interfacial compositions (X_{Ai} and Y_{Ai}) and the molar flux of SO_2.

3) A liquid mixture containing n-heptane and n-octane is to be distilled in a column at a constant pressure of 101.325 kPa. The following thermodynamic data is available for the system:

Temperature (°C)	**Vapor Phase of Pure n-Heptane** (kPa)	**Vapor Phase of Pure n-Octane** (kPa)
98.4	101.325	44.396
105	125.323	55.595
110	139.988	64.528
115	159.987	74.795
120	179.985	86.659
125.6	205.316	101.325

Assuming ideal liquid and vapor behavior, obtain an equilibrium relation between gas and liquid phase for the system and plot the equilibrium diagram.

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
Atomic # → 80
Symbol → Hg
Avg. Mass → 200.59

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)