16-CHEM-A3, HEAT and MASS TRANSFER

DECEMBER 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 solution containing 500 kg of Na_2SO_4 in 2500 kg of water is cooled from 50 °C to 10 °C in an agitated mild steel vessel of mass 750 kg. At 10 °C, the solubility of the anhydrous salt is 8.9 kg per 100 kg of water and the stable crystalline phase is $Na_2SO_4.10H_2O$. If 2% of the water initially present is lost by evaporation during cooling, estimate the heat that must be removed.

DATA: Heat of solution at 18 °C = -78.5 kJ/mol

Specific heat capacity of Na_2SO_4 solution = 3.6 kJ/kg K

Specific heat capacity of mild steel = 0.5 kJ/kg K

2) A vertical plate (15 cm x 15 cm) at 40 °C is exposed to ambient still air at 20 °C. Compare the free convection heat transfer rate from the plate to the forced convection heat transfer rate that would result at a velocity equal to twice the maximum velocity under free convection conditions. The thermo-physical properties of dry air at atmospheric pressure are given below:

T $[K]$	ρ $\left[\frac{kg}{m^3}\right]$	μ $\left[10^{-6}\frac{N\cdot s}{m^2}\right]$	κ $\left[10^{-3}\frac{W}{m\cdot K}\right]$	C_p $\left[\frac{J}{kg\cdot K}\right]$	ρ/μ $\left[10^3\frac{s}{m^2}\right]$	$g\beta/(\nu\alpha)$ $\left[10^6\frac{1}{m^3\cdot K}\right]$	α $\left[10^{-6}\frac{m^2}{s}\right]$
200	1.7690	13.36	18.10	1006.4	132.4	638.6	10.17
210	1.6842	13.92	18.95	1006.1	121.0	505.2	11.18
220	1.6071	14.47	19.80	1005.7	111.1	404.2	12.25
230	1.5368	15.01	20.63	1005.6	102.4	327.0	13.35
240	1.4728	15.54	21.45	1005.5	94.8	267.3	14.49
250	1.4133	16.06	22.26	1005.4	88.0	220.4	15.67
260	1.3587	16.57	23.05	1005.5	82.0	183.3	16.87
270	1.3082	17.07	23.84	1005.5	76.6	153.6	18.12
280	1.2614	17.57	24.61	1005.7	71.8	129.6	19.40
290	1.2177	18.05	25.38	1006.0	67.5	110.1	20.72
300	1.1769	18.53	26.14	1006.3	63.5	94.1	22.07
310	1.1389	19.00	26.87	1006.8	59.9	80.9	23.43
320	1.1032	19.46	27.59	1007.3	56.7	70.0	24.83
330	1.0697	19.92	28.30	1007.9	53.7	60.8	26.25
340	1.0382	20.37	29.00	1008.5	51.0	53.1	27.70
350	1.0086	20.81	29.70	1009.2	48.5	46.5	29.18
360	0.9805	21.25	30.39	1010.0	46.1	41.0	30.69
370	0.9539	21.68	31.07	1010.9	44.0	36.2	32.22
380	0.9288	22.11	31.73	1012.0	42.0	32.1	33.76
390	0.9050	22.52	32.39	1013.0	40.2	28.6	35.33
400	0.8822	22.94	33.05	1014.2	38.5	25.5	36.94

3) A shell-and-tube heat exchanger consists of 120 tubes of 22-mm internal diameter and length of 2.5 m. It is operated as a single-pass condenser with benzene condensing at a temperature of 350 K on the outside of the tubes and water at inlet temperature of 290 K passing through the tubes. Initially there is no scale on the walls, and a rate of condensation of 4 kg/s is obtained with a water velocity of 70 cm/s through the tubes. After prolonged operation, a scale resistance of 2×10^{-4} m^2 K/W is formed on the inner surface of the tubes. Assuming the heat transfer coefficient on the water side is proportional to 0.8 power of velocity and the heat transfer coefficient for condensing vapor is 2.25 kW/m^2 K based on the inside area, to what value must the water velocity be changed in order to maintain the same rate of condensation? The latent heat of vaporization of benzene is 400 kJ/kg.

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 333 K = 2383 kJ/kg

PART B – MASS TRANSFER

1) A 4 cm^3 mixture formed by adding 2 cm^3 of acetone (CH_3-CO-CH_3) to 2 cm^3 dibutyl phthalate ($CO_2C_4H_9$-C_6H_4-$CO_2C_4H_9$) is contained in a 6 mm diameter vertical glass tube immersed in a thermostat maintained at 42 °C. A stream of air at 42 °C and 101.325 kPa pressure is passed over the open top of the tube to maintain a zero-partial pressure of acetone vapor at that point. The liquid level is initially 11.5 mm below the top of the tube and the acetone vapor is transferred to the air stream by molecular diffusion alone. The dibutyl phthalate can be regarded as completely non-volatile and the partial pressure of acetone vapor may be calculated from Raoult's law on the assumption that the density of dibutyl phthalate is sufficiently greater than that of acetone for the liquid to be completely mixed.

Assuming the vapor is ideal and neglecting the effects of bulk flow in the vapor, calculate the time taken for the liquid level to fall to 5 cm below the top of the tube.

DATA: Vapor pressure of acetone at 42 °C = 60.5 kPa
Diffusivity of acetone vapor in air at 42 °C = 0.123 cm^2/s
Density of liquid acetone = 764 kg/m^3
Density of liquid dibutyl phthalate = 1048 kg/m^3

2) The heat transfer correlation for a liquid flowing over a single cylinder is given by the following equation for Nusselt number (Nu):

$$Nu = h\,D/k = (0.506\,Re^{0.5} + 0.00141\,Re)\,Pr^{0.33}$$

where

h → heat-transfer coefficient

D → diameter of cylinder

k → thermal conductivity of cylinder

Re → Reynolds number = $D\,v\,\rho/\mu$

Pr → Prandtl number = $C_p\,\mu/k$

C_p → specific heat capacity of liquid

μ → viscosity of liquid

ρ → density of liquid

v → velocity of liquid

The above equation, in association with the Chilton-Colburn analogy, can be used to predict the mass-transfer coefficient for a cylinder.

Estimate the mass-transfer coefficient (k_L) at 27 °C for the dissolution of sodium chloride from a cast cylinder (diameter = 1.5 cm) made of solid sodium chloride (NaCl) and placed perpendicular to a flowing stream of water at a velocity of 10 m/s.

<u>DATA</u>:

Binary liquid diffusivity (D_{AB}) at 18 °C = 1.26×10^{-5} cm²/s

Viscosity of water at 18 °C = 1.073×10^{-3} Pa.s

Viscosity of water at 27 °C = 8.76×10^{-4} Pa.s

Density of water = 996 kg/m³

3) A mixture of benzene and toluene containing 44% mass of benzene is separated in a distillation column at 1 atm and reflux ratio of 4 to give a product of 96% mass benzene and a waste of 4% mass toluene. The equilibrium mole fraction data for benzene at 1 atm pressure is as follows:

Vapor Mole Fraction	Liquid Mole Fraction
0.21	0.1
0.37	0.2
0.51	0.3
0.64	0.4
0.72	0.5
0.79	0.6
0.86	0.7
0.91	0.8
0.96	0.9
0.98	0.95

(a) Calculate the mole fraction on the second plate of the distillation column from the top.

(b) Determine the number of plates required and the position of the feed if supplied to the column as liquid at its boiling point of 95 °C.

(c) Find the minimum reflux ratio possible.

(d) Find the minimum number of plates required.

(e) If the feed is fed to the distillation column at 15 °C, find the number of plates required if the reflux ratio remains unchanged.

The Periodic Table of the Elements

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

Key:

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)

10 MM/CM