16-CHEM-A3, HEAT and MASS TRANSFER

MAY 2018

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** scientific 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) An organic liquid is boiling at 340 K on the inside of a 3-mm thick metal surface (thermal conductivity = 42 W/m.K). The outside of the surface is heated by condensing steam. The coefficients of heat transfer from the inner metal surface to the boiling liquid depends upon the temperature differences as listed in the table below:

Temperature Difference Between Metal Surface and Boiling Liquid (in K)	**Heat Transfer Coefficient for Metal Surface to Boiling Liquid** (in $kW/m^2.K$)
22.2	4.43
27.8	5.91
33.3	7.38
36.1	7.30
38.9	6.81
41.7	6.36
44.4	5.73
50.0	4.54

Assuming the heat transfer coefficient from the condensing steam to outside metal surface is constant at 11 $kW/m^2.K$, find the value of steam temperature would give a maximum rate of evaporation.

2) The surface temperature of a vertical plate is maintained at 390 K. Calculate the heat transfer coefficient at a distance of 45 cm from the bottom of the plate for the following assuming ideal gas behavior:

a) **[12.5 points]** Oxygen at 290 K.

b) **[12.5 points]** Hydrogen at 290 K.

Table B.4 Thermophysical Properties of Gases at Atmospheric Pressure* *(continued)*

T (K)	ρ (kg m^{-3})	C_p (kJ kg^{-1} K^{-1})	$\eta \times 10^7$ (N s m^{-2})	$\nu \times 10^6$ (m^2 s^{-1})	$k \times 10^3$ (W m^{-1} K^{-1})	$\alpha \times 10^6$ (m^2 s^{-1})	Pr
Hydrogen (H_2)							
300	0.08078	14.31	89.6	111	183	158	0.701
400	0.06059	14.48	108.2	179	226	258	0.695
500	0.04848	14.52	126.4	261	266	378	0.691
600	0.04040	14.55	142.4	352	305	519	0.678
700	0.03643	14.61	157.8	456	342	676	0.675
800	0.03030	14.70	172.4	569	378	849	0.670
900	0.02694	14.83	186.5	692	412	1030	0.671
1000	0.02424	14.99	201.3	830	448	1230	0.673
1100	0.02204	15.17	213.0	966	488	1460	0.662
1200	0.02020	15.37	226.2	1120	528	1700	0.659
1300	0.01865	15.59	238.5	1279	568	1955	0.655
1400	0.01732	15.81	250.7	1447	610	2230	0.650
1500	0.01616	16.02	262.7	1626	655	2530	0.643
1600	0.0152	16.28	273.7	1801	697	2815	0.639
1700	0.0143	16.58	284.9	1992	742	3130	0.637
1800	0.0135	16.96	296.1	2193	786	3435	0.639
1900	0.0128	17.49	307.2	2400	835	3730	0.643
2000	0.0121	18.25	318.2	2630	878	3975	0.661
Nitrogen (N_2)							
300	1.1233	1.041	178.2	15.86	25.9	22.1	0.716
400	0.8425	1.045	220.4	26.16	32.7	37.1	0.704
500	0.6739	1.056	257.7	38.24	38.9	54.7	0.700
600	0.5615	1.075	290.8	51.79	44.6	73.9	0.701
700	0.4812	1.098	321.0	66.71	49.9	94.4	0.706
800	0.4211	1.122	349.1	82.90	54.8	116	0.715
900	0.3743	1.146	375.3	100.3	59.7	139	0.721
1000	0.3368	1.167	399.9	118.7	64.7	165	0.721
1100	0.3062	1.187	423.2	138.2	70.0	193	0.718
1200	0.2807	1.204	445.3	158.6	75.8	224	0.707
1300	0.2591	1.219	466.2	179.9	81.0	256	0.701
Oxygen (O_2)							
300	1.284	0.920	207.2	16.14	26.8	22.7	0.711
400	0.9620	0.942	258.2	26.84	33.0	36.4	0.737
500	0.7698	0.972	303.3	39.40	41.2	55.1	0.716
600	0.6414	1.003	343.7	53.59	47.3	73.5	0.729
700	0.5498	1.031	380.8	69.26	52.8	93.1	0.744
800	0.4810	1.054	415.2	86.32	58.9	116	0.743
900	0.4275	1.074	447.2	104.6	64.9	141	0.740
1000	0.3848	1.090	477.0	124.0	71.0	169	0.733
1100	0.3498	1.103	505.5	144.5	75.8	196	0.736
1200	0.3206	1.115	532.5	166.1	81.9	229	0.725
1300	0.2960	1.125	588.4	188.6	87.1	262	0.721

*Condensation of Table A.4 in F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 3rd edition, John Wiley, New York, NY, 1990.

3) 0.9 kg/s of air is warmed from 283 K to 366 K by passing it through a bank of pipes (20 rows with 20 pipes/row). The pipes are arranged with center-to-center spacing, in both directions, equal to twice the pipe diameter. Flue gas, entering at 700 K and leaving at 366 K, with a free flow of mass velocity of 10 $kg/m^2.s$, is passed at right angles across the outside of pipes. For simplicity, the outside and inner diameters of the pipe may be taken as 12 mm. Values for thermal conductivity (k) and viscosity (μ), which may be used for both air and flue gas, are given below:

Temperature, T (in K)	**Thermal Conductivity, k** (in W/m.K)	**Viscosity, μ** (in $mN.s/m^2$)
250	0.022	0.0165
500	0.044	0.0276
800	0.055	0.0367

Neglecting gas radiation, pipe wall and scale resistances, calculate the length of each pipe.

DATA: Specific heat capacity of air and flue gases = 1 kJ/kg.K
Heat transfer arrangement factor for in-line pipes = 0.95

PART B – MASS TRANSFER

1) Trichloroacetic acid (CCl_3COOH) is diffusing across a 2-mm thick non-diffusing methanol (CH_3OH) solution at 20 °C. The concentrations of trichloroacetic acid on the opposite sides of the methanol film are 6% and 2% by weight. The density of 6% acid solution and 2% acid solution are 1012 and 1003 kg/m^3, respectively. The diffusivity of trichloroacetic acid in methanol at 20 °C is 1.862×10^{-9} m^2/s. Calculate the rate of diffusion of trichloroacetic acid.

2) A solution of 25% by mole of acetic acid in water was distilled at atmospheric pressure until 60% by mole of the liquid was distilled. The equilibrium data for acetic acid-water system at 1 atm pressure is given below:

Mole Fraction of Acetic Acid in Liquid Phase	Mole Fraction of Acetic Acid in Vapor Phase
0.07	0.05
0.15	0.11
0.27	0.20
0.50	0.38
0.62	0.49
0.72	0.60
0.82	0.73
0.90	0.84
1.00	1.00

Compute the compositions of the distillate and the residue.

3) A gas mixture at 20 °C and 1.013 x 10^5 Pa flows through a packed tower at a rate of 1 m^3/s. The gas mixture contains 10% by mole of soluble gas A (molecular weight = 64 g/mole) and rest inert (molecular weight = 30 g/mole) is to be scrubbed in a countercurrent operation with water to remove 95% of gas A. The tower is packed with 25 mm stoneware Raschig rings and the following equilibrium is available at 1.013 x 10^5 Pa:

Moles of A/Mole of Water	Moles of A/Mole of Inert Gas
0.001	0.024
0.002	0.055
0.003	0.090
0.004	0.129
0.005	0.170
0.006	0.212

The following relationship holds under the operating conditions:

$$[538\, G'^2\, \mu'^{0.2}_L] / [g_c\, \rho_G\, \rho_L] = 0.052\, (L'/G')(\rho_G/\rho_L)^{0.5}$$

where G' → Mass velocity of gas phase in $kg/m^2.s$

L' → Mass velocity of liquid phase in $kg/m^2.s$

ρ_G → Density of gas phase in kg/m^3

ρ_L → Density of liquid phase/solution in kg/m^3

g_c → Gravitational constant = 9.807 $kg_m.m/kg_f.s^2$

μ'_L → Viscosity of solution in centipoise (cP)

(a) **[15 points]** Determine the minimum liquid rate in kg/s.

(b) **[10 points]** Estimate the tower diameter for a liquid rate 20% in excess of the minimum and the operating gas velocity to be 60% of that at the flooding point.

DATA: Density of the solution (ρ_L) = 1020 kg/m^3

Viscosity of the solution (μ'_L) = 0.902 cP

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)