

**16-CHEM-A3, HEAT and MASS TRANSFER**

**DECEMBER 2017**

**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) Water in a tank at 15 °C is heated by passing steam through a 60-cm long, 40-mm diameter pipe placed in water. The surface temperature of the pipe is maintained at 85 °C. The following empirical correlations for Nusselt number (Nu) as a function of Grashoff number (Gr) and Prandtl number (Pr) may be used:

$$\text{Nu} = C (\text{Gr Pr})^m$$

where C and m are constants. The values of C and m are as follows:

$$C = 0.53 \text{ and } m = 0.25 \text{ for } 10^4 < \text{Gr Pr} < 10^9$$

$$C = 0.13 \text{ and } m = 0.33 \text{ for } \text{Gr Pr} > 10^9$$

- (a) [13 points] Find the heat loss from the pipe if it is kept horizontal.  
(b) [12 points] Find the heat loss from the pipe if it is kept vertical.

DATA:            Density of water = 988 kg/m<sup>3</sup>  
                         Thermal conductivity of water = 0.647 W/m.K  
                         Viscosity of water = 5.493 x 10<sup>-4</sup> kg/m.s  
                         Specific heat capacity of water = 4.178 kJ/kg.K  
                         Coefficient of volume expansion of water = 5.1 x 10<sup>-4</sup> K<sup>-1</sup>

- 2) A pipe (outside diameter = 30 cm) is covered with two layers of insulation. The thermal conductivity of the first layer, which is on the outside, is 0.105 W/m.K and 40 mm thick. The thermal conductivity of the second layer, which is on the inside, is 0.105 W/m.K and 50 mm thick. The inner and outer surface temperatures of the insulation are 350 °C and 50 °C, respectively.
- (a) [10 points] Estimate the heat loss per meter length of the pipe.
  - (b) [5 points] Estimate the heat loss per m<sup>2</sup> of outer insulation surface.
  - (c) [10 points] Estimate the temperature of the surface between the two layers of insulation.
- 3) A heat exchanger is to be designed to heat water flowing at a rate of 1720 kg/hr from 20 °C to 45 °C using steam condensing at 110 °C on the outside surface of 4-meter long brass tubes (thermal conductivity = 111.65 W/m.K, outside diameter = 25 mm, inside diameter = 22.5 mm). The velocity of water is 61.2 m/min and the weight of steam condensed is 1.25 kg/s. Find the number of brass tubes required to heat water from 20 °C to 45 °C.

DATA:

- Density of water = 995.7 kg/m<sup>3</sup>
- Thermal conductivity of water = 0.617 W/m.K
- Kinematic viscosity of water =  $6.59 \times 10^{-7}$  m<sup>2</sup>/s
- Specific heat capacity of water = 4.174 kJ/kg.K
- Latent heat of vaporization of water = 2230 kJ/kg
- Steam side film heat transfer coefficient = 4650 W/m<sup>2</sup>.K

**PART B – MASS TRANSFER**

- 1) It is desired to separate a mixture containing benzene and toluene at a constant pressure of 101.32 kPa absolute using the following vapor pressure data:

Temperature, in °C	Vapor Pressure of Benzene, in kPa	Vapor Pressure of Toluene, in kPa
80.0	101.32	-
82.9	108.12	41.86
85.0	117.60	46.00
87.0	127.60	50.40
90.5	138.25	55.20
93.3	149.72	60.26
96.1	161.85	65.86
99.0	174.65	71.73
101.6	188.25	78.00
104.5	202.65	84.66
107.2	216.65	91.86
110.0	234.11	99.59
110.1	-	101.32

- (a) [15 points] Compute the vapor-liquid equilibrium data at 101.32 kPa absolute.  
 (b) [10 points] Find an empirical relation between liquid and vapor phase composition.

- 2) An air-ammonia mixture flowing at a rate of 20 mol/hr and containing 5% NH<sub>3</sub> by volume is being scrubbed in a countercurrent manner with 2N sulfuric acid in a wetted wall column (internal diameter = 15 mm, length = 70 cm) operating at 20 °C and 101.3 kN/m<sup>2</sup>. Under these conditions, 90% of NH<sub>3</sub> is absorbed, and the change in acid concentration can be neglected.
- (a) [12 points] Calculate the value of mass transfer coefficient,  $k_G$ .
- (b) [13 points] If the value of the heat transfer coefficient ( $h$ ) in a similar setup with identical operating conditions is 75.2 kcal/hr.m<sup>2</sup>.°C, then estimate the value of mass transfer coefficient ( $k_G$ ) from Chilton-Colburn analogy.

DATA:            Diffusivity of NH<sub>3</sub> in air at 20 °C =  $2.2 \times 10^{-5}$  m<sup>2</sup>/s  
                      Specific heat capacity of air at 20 °C = 238 cal/kg.°C  
                      Scmidt number (Sc) of air-NH<sub>3</sub> mixture at 20 °C = 0.67  
                      Prandtl number (Pr) of air at 20 °C = 0.70

- 3) Air is flowing at a velocity of 2.5 m/s over a horizontal water surface 2 meters long. The total pressure is 0.98 kgf/m<sup>2</sup> and the partial pressure of water vapor in the air is 10 mm Hg. The relative humidity of air is 33.3%. Calculate the loss of water per hour per unit area from the horizontal water surface.

DATA:            Diffusion coefficient of water vapor in air = 7.0 cm<sup>2</sup>/hr  
                      Kinematic viscosity of air =  $1 \times 10^{-3}$  cm<sup>2</sup>/hr

# The Periodic Table of the Elements

		Atomic #																																																																																		
		Element name																																																																																		
		Symbol																																																																																		
		Avg. Mass																																																																																		
Hydrogen 1 H 1.01	2	Mercury 80 Hg 200.59																																																																																		
Lithium 3 Li 6.94	Beryllium 4 Be 9.01	5	6	7	8	9	10	11	12	13	14	15	16	17	Helium 2 He 4.00																																																																					
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	Lanthanum 57 La 138.91	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)	Actinium 89 Ac (227)	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	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.04	Francium 87 Fr (223)	Radium 88 Ra (226)	Actinium 89 Ac (227)	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	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.04	Francium 87 Fr (223)	Radium 88 Ra (226)	Actinium 89 Ac (227)	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	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.04

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

\*lanthanides  
\*\*actinides