National Exams December 2015

04-CHEM-A3 (Mass Transfer Operations)

Three-Hour 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.

4) The examination is in three parts – Part A (Questions 1 and 2)
Part B (Questions 3 and 4)
Part C (Questions 5 to 7)

5) Answer **ONE** question from Part A, **ONE** question from Part B, and **TWO** questions from Part C. **FOUR** questions constitute a complete paper.

6) Each question is of equal value.

PART A

1) A mixture of nitrogen gas (A) and helium gas (B) at 298 K is diffusing through a capillary 0.1 m long in an open system with a diameter of 10 μm. The mole fractions are constant at $X_{A1} = 1.0$ and $X_{A2} = 0$, and the binary diffusivity (D_{AB}) at 1 atm is 6.98×10^{-5} m^2/s.

   (a) Calculate the Knudsen diffusivities (D_{KA} and D_{KB}) at total pressure of 0.001, 0.1 and 10 atm.

   (b) Calculate the steady-state flux N_A at total pressure of 0.001, 0.1 and 10 atm.

   (c) Plot steady-state flux N_A versus total pressure P on a log-log paper.

   (d) Plot the limiting lines at lower pressures (Knudsen diffusion) and very high pressures (molecular diffusion) on the same log-log plot from part (c).

   (e) Calculate the steady-state flux N_A for Knudsen diffusion and molecular diffusion regions.

2) A total of 5 grams of wet microorganisms having a density of 1100 kg/m^3 and a diameter of 0.667 μm are added to 100 ml aqueous solution at 37 °C in a shaker flask for fermentation. Air can enter through a porous stopper.

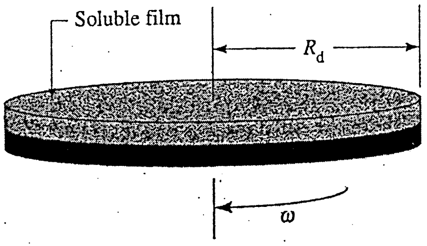
   (a) Calculate the maximum rate possible for mass transfer of oxygen in kg moles of O_2 per second to the surface of the microorganisms. Assume that the solution is saturated with air at 101.32 kPa absolute pressure.

   (b) By material balances on other nutrients, the actual utilization of O_2 by the microorganisms is 6.3×10^{-6} kg moles per second. What would be the actual concentration of O_2 in the solution as percent saturation during the fermentation?

   <u>DATA</u>: Solubility of O_2 from air in water at 37 °C = 2.26×10^{-4} kg moles/m^3
   Diffusivity of O_2 in water at 37 °C = 3.25×10^{-9} m^2/s
   Density of water at 37 °C = 994 kg/m^3
   Viscosity of water at 37 °C = 6.947×10^{-4} Pa.s = 6.947×10^{-4} kg/m.s
   Density of air at 37 °C = 1.13 kg/m^3

PART B

3) A “spinning disk” mass transfer device is designed as shown in the figure below.



A solid disk rotates about an axis normal to its circular face and is immersed in a large volume of fluid. Except for the motion induced by the rotation of the disk, there is no imposed convective flow in the system. The surface of the disk is coated with a solid film of a material that is soluble in the surrounding fluid. A significant motion is induced by the rotation of the disk, and this motion gives rise to significant convective mass transfer from the disk surface.

Studies have shown that the convective mass transfer coefficient (k_c, in cm/s) is given by the equation

$$k_c = 0.62\,(D_{AB})^{0.667}\,(\nu)^{-0.167}\,(\omega)^{0.5}$$

where D_{AB} → diffusion coefficient of the solute in the fluid (in cm^2/s)

☐ ν → kinematic viscosity (μ/ρ) of the fluid (in cm^2/s)

☐ ω → rotational speed of the disk (in rad/s)

(a) Define Reynolds number (Re) and Schmidt number (Sc) in terms of the parameters D_{AB}, ν, and ω.

(b) Convert the convective mass transfer coefficient equation into the following non-dimensional form:

$$\text{Sherwood number} = Sh = A\,(Re)^n\,(Sc)^m$$

(c) Obtain the values of constant A, n, and m.

4) 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 300 K 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 291 K = 1.26×10^{-9} m²/s

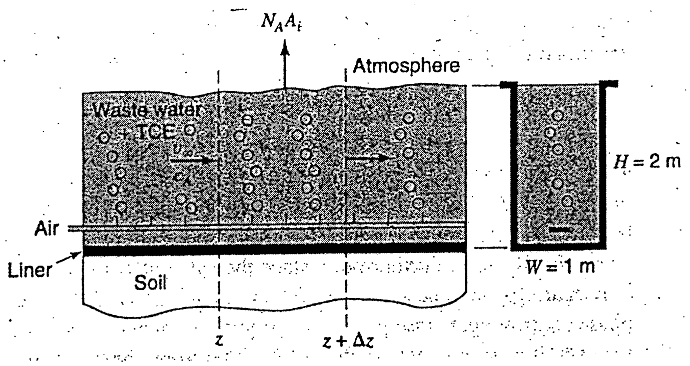
Viscosity of water at 291 K = 1.073×10^{-3} Pa.s

Viscosity of water at 300 K = 8.76×10^{-4} Pa.s

Density of water = 996 kg/m³

PART C

5) A very simple process to treat contaminated wastewater before discharge to a lake or river is the remediation trench as shown in the figure below.



The trench consists of a narrow outdoor open channel with an air sparger aligned along the bottom of the trench. Wastewater containing a volatile contaminant dissolved in the water enters one end of the trench. As the wastewater flows down the trench, the aeration gas strips out the dissolved volatile solute and transfer it to the surrounding atmosphere by an interphase mass-transfer process. Consequently, the concentration of the solute in the wastewater decreases down the length of the trench. Remediation trenches can be long, and may extend from a holding pond to the discharge point.

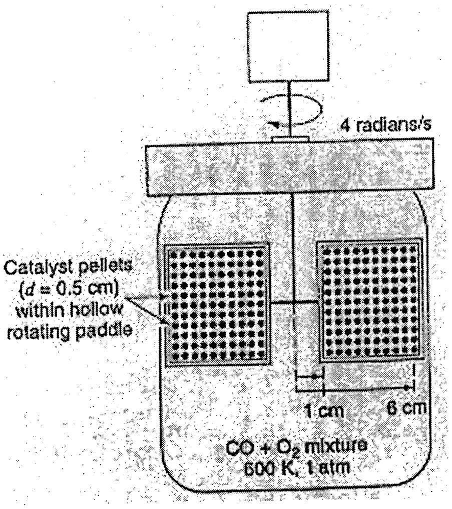
We wish to design an aerated remediation trench to treat wastewater contaminated with trichloroethylene (C_2HCl_3) at a concentration of 50 mg/L of wastewater. The process temperature is 293 K and the total system pressure is 1 atm. The trench is an open duct of 1 meter width (W) and 2 meters depth (H), and the volumetric flow rate of wastewater added to the trench is 0.1 m^3/s. Air is sparged into the bottom of the duct at a rate that provides a gas holdup of 0.02 m^3 of gas/m^3 of water, and the average bubble diameter is 1 cm (d_b).

Determine the length of trench necessary to reduce the effluent trichloroethylene concentration to 0.05 mg/L of treated wastewater.

DATA:

Henry's law constant for trichloroethylene in water = 9.97 atm m^3/kg mole
Diffusivity of the air in wastewater (D_{AB}) = 8.9×10^{-10} m^2/s
Viscosity of the wastewater = 9.93×10^{-4} kg/m.s
Density of the wastewater = 998.2 kg/m^3
Density of the air = 1.19 kg/m^3

6) Consider the well-mixed, continuous-flow spinning catalyst paddle reactor shown in the figure below for carrying out catalytic gas-solid reactions under controlled hydrodynamic conditions.



Two hollow paddles, each with exposed faces of 5 cm in height and width, are mounted on an impeller shaft 1 cm from centerline. Spherical, non-porous solid catalyst pellets of 0.5 cm diameter are held within each paddle by a screen. As the impeller shaft rotates, gas flows through the paddle and over each spherical pellet. Since there is only one layer of spherical pellets within the hollow impeller paddle and individual pellets do not touch one another, mass transfer can be analyzed with respect to a single particle and not a packed bed of particles. Carbon monoxide gas diluted into a large amount of oxygen gas is fed into the reactor. The temperature and total pressure inside the vessel are 600 K and 1 atm. The carbon monoxide instantaneously reacts with oxygen on the outer surface of the catalyst pellet to form carbon dioxide.

(a) Using boundary-layer theory of convective mass transfer, estimate the mean gas-film mass transfer coefficient (in cm/s) for carbon monoxide over the whole width of the paddle for a fixed rotation rate (□) of 4 radians/s.

(b) Repeat the calculation for carbon dioxide.

Table K.2 Lennard–Jones force constants calculated from viscosity data†

Compound	Formula	ϵ_A/κ, in (K)	σ, in Å
Acetylene	C_2H_2	185	4.221
Air		97	3.617
Argon	A	124	3.418
Arsine	AsH_3	281	4.06
Benzene	C_6H_6	440	5.270
Bromine	Br_2	520	4.268
i-Butane	C_4H_{10}	313	5.341
n-Butane	C_4H_{10}	410	4.997
Carbon dioxide	CO_2	190	3.996
Carbon disulfide	CS_2	488	4.438
Carbon monoxide	CO	110	3.590
Hydrogen iodide	HI	324	4.123
Iodine	I_2	550	4.982
Krypton	Kr	190	3.60
Methane	CH_4	136.5	3.822
Methanol	CH_3OH	507	3.585
Methylene chloride	CH_2Cl_2	406	4.759
Methyl chloride	CH_3Cl	855	3.375
Mercuric iodide	HgI_2	691	5.625
Mercury	Hg	851	2.898
Neon	Ne	35.7	2.789
Nitric oxide	NO	119	3.470
Nitrogen	N_2	91.5	3.681
Nitrous oxide	N_2O	220	3.879
n-Nonane	C_9H_{20}	240	8.448
n-Octane	C_8H_{18}	320	7.451
Oxygen	O_2	113	3.433

Collision integral Ω_D

$\frac{kT}{\varepsilon_{12}}$	Ω_D	$\frac{kT}{\varepsilon_{12}}$	Ω_D	$\frac{kT}{\varepsilon_{12}}$	Ω_D
0.30	2.662	1.65	1.153	4.0	0.8836
0.35	2.476	1.70	1.140	4.1	0.8788
0.40	2.318	1.75	1.128	4.2	0.8740
0.45	2.184	1.80	1.116	4.3	0.8694
0.50	2.066	1.85	1.105	4.4	0.8652
0.55	1.966	1.90	1.094	4.5	0.8610
0.60	1.877	1.95	1.084	4.6	0.8568
0.65	1.798	2.00	1.075	4.7	0.8530
0.70	1.729	2.1	1.057	4.8	0.8492
0.75	1.667	2.2	1.041	4.9	0.8456
0.80	1.612	2.3	1.026	5.0	0.8422
0.85	1.562	2.4	1.012	6	0.8124
0.90	1.517	2.5	0.9996	7	0.7896
0.95	1.476	2.6	0.9878	8	0.7712
1.00	1.439	2.7	0.9770	9	0.7556
1.05	1.406	2.8	0.9672	10	0.7424
1.10	1.375	2.9	0.9576	20	0.6640
1.15	1.346	3.0	0.9490	30	0.6232
1.20	1.320	3.1	0.9406	40	0.5960
1.25	1.296	3.2	0.9328	50	0.5756
1.30	1.273	3.3	0.9256	60	0.5596
1.35	1.253	3.4	0.9186	70	0.5464
1.40	1.233	3.5	0.9120	80	0.5352
1.45	1.215	3.6	0.9058	90	0.5256
1.50	1.198	3.7	0.8998	100	0.5130
1.55	1.182	3.8	0.8942	200	0.4644
1.60	1.167	3.9	0.8888	400	0.4170

7) A process is being developed to produce carbonated beverages. As part of this process, a packed-bed absorption tower is used to dissolve carbon dioxide gas into water. In the present process, pure mountain spring water containing no dissolved CO_2 enters the top of the tower at a flow rate of 5 kg moles/min. Pure CO_2 gas at 2 atm is also fed to the top of the tower at a flow rate of 1 kg mole/min. As the liquid flows down the tower, CO_2 gas absorbs into water, and the dissolved CO_2 concentration increases down the length of the bed. The carbonated water and the unused CO_2 gas exit the bottom of the tower. The absorption process is liquid-film controlling since only pure CO_2 is present in the gas phase. The tower is packed with 1-inch ceramic saddles, and the inner tower diameter is 0.25 m. The temperature is maintained at 20 °C, and Henry's law constant for the dissolution of CO_2 gas in water is 25.4 atm.m^3/kg mole.

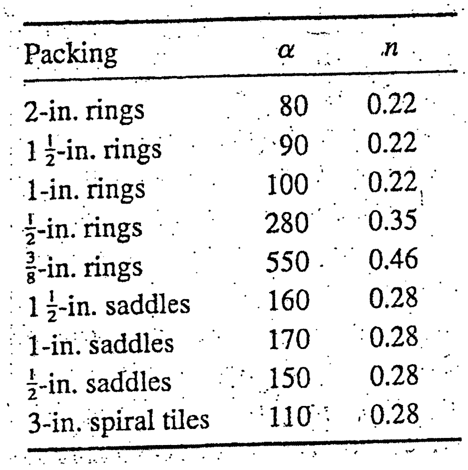
(a) What is the liquid-phase mass-transfer coefficient, k_La, for CO_2 in water flowing through the packed bed?

(b) The desired concentration of dissolved CO_2 in the outlet liquid is 0.075 kg mole/m^3, which corresponds to 95% of the saturation value for dissolved CO_2 in water under CO_2 partial pressure of 2 atm and 20 °C. What is the depth of packing necessary to attain this outlet concentration?

DATA: Density of liquid water = 998.2 kg/m^3

Viscosity of liquid water = 9.93 x 10^{-4} kg/m.s

Binary diffusivity = 1.77 x 10^{-9} m^2/s



Packing	α	n
2-in. rings	80	0.22
$1\frac{1}{2}$-in. rings	90	0.22
1-in. rings	100	0.22
$\frac{1}{2}$-in. rings	280	0.35
$\frac{3}{8}$-in. rings	550	0.46
$1\frac{1}{2}$-in. saddles	160	0.28
1-in. saddles	170	0.28
$\frac{1}{2}$-in. saddles	150	0.28
3-in. spiral tiles	110	0.28

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)