ENV 6438: PHYSICAL & CHEMICAL PROCESSES FOR DRINKING WATER TREATMENT
MIDTERM EXAMINATION

Spring 2020 | University of South Florida
Wednesday, March 11 | Prof. J.A. Cunningham

Instructions:

1. You may read these instructions, but do not turn the page or begin working until instructed to do so.
2. There are 4 questions, some with sub-parts. Answer all four questions.
3. Point values are indicated for each question. The total number of points is 100.
4. Unit conversion factors and other potentially useful items are provided on the back of this page.
5. Write your answers on your own paper. Make sure your name is indicated clearly. Staple your pages together neatly when you turn in your work.
6. Show your work and state any important assumptions you make. I cannot award partial credit if I can't follow what you did.
7. Report a reasonable number of significant digits in your answers.
8. Include units in your answers. An answer without proper units is not correct!
9. You are allowed one sheet of 8.5-by-11-inch paper (or A4 paper) with hand-written notes. You may write on both sides of that paper. However, mechanical reproductions (photo-copying, laser printing, scanning, etc.) are not allowed; all notes must be hand-written.
10. A calculator is recommended, but it may not be pre-programmed with formulae from class. Other electronic devices are not permitted.
11. Time limit: 60 minutes, plus ~5 minute "bonus" time. Stop working when asked. If you continue working after time has been called, you will be penalized at a rate of 2 points per minute.
12. Don't cheat. Cheating will result in appropriate disciplinary action according to university policy. More importantly, cheating indicates a lack of personal integrity.
13. Hints:
    - Read each question carefully and answer the question that is asked.
    - Watch your units. If you take good care of your units, they will take good care of you.
    - Work carefully and don't rush. Work quickly, but not carelessly.
    - If you can solve the problems in order, it will help, because for some problems you will need a value calculated in a previous problem.
    - If you need a value from a previous problem, but you weren't able to solve the previous problem, pick a reasonable value and proceed. For example, "I was unable to find the pH in problem 2, but I will assume the pH is 5.0, because we know the system is slightly acidic." This will let you continue working on the remaining questions.
    - Use your time wisely. Don't spend 30 minutes on a 5-minute problem. That would be a poor use of time. Besides, it probably means that you are not seeing the proper solution procedure, so skip it and move on.

Potentially useful constants:

Ideal gas constant, *R*:	$8.314\ Pa \cdot m^3 \cdot mol^{-1} \cdot K^{-1} = 82.06 \times 10^{-6}\ atm \cdot m^3 \cdot mol^{-1} \cdot K^{-1}$
Boltzmann's constant, *k*:	1.381×10^{-23} J/K
Gravitational acceleration, *g*:	9.81 m/s^2
Molar mass of water, H_2O:	18.01 g/mole
Density of water at 18 °C:	0.9985 g/mL = 998.5 kg/m^3
Viscosity of water at 18 °C:	1.06×10^{-3} Pa·s = 1.06×10^{-3} kg/(m·s)

Potentially useful conversion factors:

Mass:	1 kg = 1000 g = 10^6 mg = 10^9 μg
	1 kg = 2.207 lb_{mass}
	1 t (metric tonne) = 1000 kg = 2207 lb_{mass}
	1 ton (English ton) = 2000 lb_{mass}
Length:	1 km = 1000 m = 10^5 cm = 10^6 mm = 10^9 μm
	1 ft = 12 in = 30.48 cm = 0.3048 m
Area :	1 ha = 10^4 m^2
Volume:	1 m^3 = 1000 L = 10^6 mL = 10^6 cm^3
	1 gal = 3.785 L
Temperature:	25 °C = 298.15 K
Pressure:	1 atm = 760 mm Hg = 760 torr = 14.7 lb_{force}/in^2 = 101,325 Pa
	1 Pa = 1 N/m^2 = 1 kg/(m•s^2)
	1 bar = 10^5 Pa
Work/Energy:	1 BTU = 1.055 kJ
Power:	1 MW = 10^6 W = 10^6 J/s = 10^6 N•m/s

Atomic Masses:

H = 1.008 g/mole	C = 12.011 g/mole	N = 14.007 g/mole	O = 15.999 g/mole
P = 30.974 g/mole	S = 32.06 g/mole	Cl = 35.453 g/mole	Br = 79.904 g/mole
Na = 22.99 g/mole	Mg = 24.31 g/mole	Al = 26.98 g/mole	K = 39.098 g/mole
Ca = 40.08 g/mole	Fe = 55.85 g/mole		

Background information:

- The city of Mudville uses the Muddy River as the source of its drinking water.
- A disaster has occurred at the Mudville Water Treatment Facility, and now most of the treatment processes are off-line. The facility is still able to operate its rapid mix (coagulation), one flocculation basin, and one sedimentation basin.
- We are worried that maybe this is not enough to safely protect the citizens of Mudville from viruses, bacteria, and protozoan cysts.
- For this exam, we will treat viruses, bacteria, and cysts as spherical particles. The diameter of viruses is 0.1 μm, the diameter of bacteria is 1.0 μm, and the diameter of cysts is 10 μm.
- The water temperature is 18 °C.
- The facility is operating at steady-state conditions.

1. (25 pts) The facility is no longer sure of the residence time in the flocculation basin, because most of the facility's instrumentation got knocked off-line during the disaster. To determine the residence time in the flocculation basin, the facility ran a tracer test. At time $t = 0$, the operators dumped a bag of tracer into the inlet of the flocculation basin, then measured the concentration of tracer exiting the basin. The operators gathered the following data.

time interval (min)	average tracer concentration during the time interval (mg/L)
0 – 10	71.7
10 – 20	36.8
20 – 40	13.5
40 – 60	8.2
60 – 80	3.0
80 – 100	0.2

Based on these data, estimate/calculate the average hydraulic residence time, τ, in the flocculation basin. Report your answer in units of min. Show your work to get full credit.

2. (40 pts) The facility is dosing the water with ferric sulfate, $Fe_2(SO_4)_3$. This coagulant results in the formation of $Fe(OH)_3$ flocs. In the flocculation basin, we hope that the $Fe(OH)_3$ flocs collide with the pathogens.

   - The concentration of $Fe(OH)_3$ flocs in the flocculation basin is $N_F = 1.0\times10^{10}$ flocs/m^3.
   - The volume fraction of flocs in the flocculation basin is $\Omega = 3.0\times10^{-5}$.
   - For the purposes of this exam, we will pretend that the $Fe(OH)_3$ flocs are spherical, and that all the $Fe(OH)_3$ flocs have the same diameter.
   - The flocculation basin can be treated as a completely mixed flow reactor. (It is possible to show that the data from problem 1 are consistent with this assumption.)
   - The average velocity gradient in the flocculation basin is $G = 20\ s^{-1}$. (It is a bit low because the impeller was damaged in the disaster.)
   - Density of the flocs and the pathogens is about 1700 kg/m^3.

   a. (8 pts) Estimate/calculate the diameter of the $Fe(OH)_3$ flocs, in units of m and μm.

   - We will use the symbol β to denote the second-order rate coefficient for the rate of collisions between flocs and pathogens. Specifically, β_{FV} is the rate coefficient for collisions between flocs and viruses, β_{FB} is the coefficient for collisions between flocs and bacteria, and β_{FC} is the coefficient for collisions between flocs and protozoan cysts.
   - The concentration of viruses entering the flocculation basin is N_V^{in}. The concentration of bacteria entering is N_B^{in}. The concentration of protozoan cysts entering is N_C^{in}.
   - The "sticking efficiency" for collisions between flocs and pathogens is α. That is, α represents the likelihood that the floc and the pathogen will adhere to each other when they collide. For this basin, assume $\alpha = 0.8$.

   b. (16 pts) Pick one of the pathogens – viruses, bacteria, or protozoan cysts. It does not matter (yet) which one you pick. *Write a material balance* (mass balance) for the *number of pathogens* in the flocculation basin. Start with

   Accumulation = Flow in – Flow out + Sources – Sinks

   and fill in appropriate mathematical expressions. Then, re-arrange the equation to derive an equation for N^{out}, the effluent concentration of pathogens exiting the flocculation basin. Your expression for N^{out} should be written in terms of N^{in}, β, N_F, α, and τ (the average hydraulic residence time of the basin). Hint: you should account for collisions between the pathogens and the flocs, but you can ignore the collisions between pathogens and pathogens. (It is probably a realistic assumption that pathogen-pathogen collisions are far less important than pathogen-floc collisions.)

problem 2 continues →

2. continued
   c. (8 pts) For viruses and bacteria, *differential settling* is the dominant mechanism for collisions between viruses and flocs. For protozoan cysts, *macroscale flocculation* is the dominant mechanism. Based on this, estimate β for whichever pathogen type you selected in part (b).

   d. (8 pts) Estimate the fractional reduction, $1 - N^{out}/N^{in}$, for the pathogen type that you chose. Is the facility doing a good job of flocculating these pathogens?

3. (25 pts) Four types of particles exit the flocculation basin: viruses, bacteria, protozoan cysts, and $Fe(OH)_3$ flocs. The $Fe(OH)_3$ flocs might be laden with pathogens, depending on how well the flocculation process worked. We hope that all four of these types of particles are effectively removed in the sedimentation basin. Consistent with problem 2, assume that the density of all particle types is 1700 kg/m^3.

   a. (15 pts) The overflow rate in the conventional sedimentation basin is 3.0 m/hr. This is a bit high because some of the basins were damaged in the disaster, so now all the water has to be routed through the one remaining basin. Based on this overflow rate, estimate/calculate the diameter of the *smallest* particle that would be 100% removed by sedimentation. In other words, particles of diameter $d_p \geq d_{min}$ will be 100% removed; estimate/calculate d_{min}. Report your answer in units of m and μm.

   b. (10 pts) Comment on how effectively you would expect each of our four particle types (viruses, bacteria, cysts, flocs) to be removed by sedimentation. Answer quantitatively for full credit, or qualitatively for partial credit.

4. (10 pts) Is the Mudville Water Treatment Facility able to adequately treat the water using just the existing treatment processes? Explain briefly, referring to your answers to problems (2) and (3). Based on your calculations, what would you tell the citizens of Mudville and the city's water department?

END OF EXAMINATION