ENV 6438: Physical & Chemical Processes for Drinking Water Treatment
Department of Civil & Environmental Engineering
University of South Florida
Cunningham **Spring 2020**

Homework #4 Due Wednesday, Feb. 26

Topic: Flocculation

Complete problem 1; then complete problem 2 <u>*or*</u> problem 3; *skip* problem 4; then complete problem 5 <u>*or*</u> problem 6

1. (45 pts) Recall from homework #3 that a city is pulling water from a river, and that the aquasol in the water has the following particle-size distribution.

particle size range (μm)	ΔN (particles/mL)
0.5 – 1	1.8×10^{11}
1 – 2	1.6×10^{10}
2 – 8	4.3×10^{8}
8 – 32	3.35×10^{6}
32 – 128	2.6×10^{4}

In homework 3, you found that the smallest size class dominates not only the number concentration, but also the mass concentration and the surface-area concentration. Therefore the city wants to be sure to get good removal of the smallest particles in their coagulation/ flocculation process. Suppose the city operates a single-stage flocculator with an average velocity gradient G = 60 s^{-1}. Also suppose the water temperature is 20 °C. For this homework, assume that the particles are spherical, and that the size given is the diameter of the spheres. (That part is different from homework 3, in which we assumed the particles were "flaky".)

Estimate the collision frequency rate, $\beta_{ij}\, n_i\, n_j$, for the smallest particles with *each* of the five different size classes. That is, estimate the rate of 1-1 collisions, of 1-2 collisions, of 1-3 collisions, of 1-4 collisions, *and* of 1-5 collisions. Then answer the following questions.

a. Report the collision frequencies (collisions per volume per time) you found for each of the five types of collisions.

problem 1 continues →

1. continued

   b. For each of the five types of collisions, indicate which of the three flocculation mechanisms (macroscale, microscale, or differential settling) is most important. Briefly (a sentence or so for each) explain why that mechanism dominates for that size class.

   c. Can any of the three flocculation mechanisms be ignored? Explain briefly.

   d. Which of the five size classes is most important in terms of removing particles of size class 1?

   e. For the purposes of analyzing flocculation, do you think it is acceptable to treat this particle suspension as *monodisperse*? Explain briefly.

2. (35 pts) Some water treatment plants employ a "maturation" basin, in which small flocs "mature" into larger flocs. We also call this a "flocculation" basin. Suppose that a particular flocculation basin at a water treatment plant is well-mixed and can be treated as a completely mixed flow reactor (CMFR) operating at steady state. Also consider the following.

   - The particle suspension entering the flocculation basin can be treated as monodisperse.
   - The particles can be considered to be spheres with a diameter of 10 μm.
   - The dominant flocculation mechanism is "macroscale" flocculation.
   - The concentration of particles in the influent water is 1.0×10^{12} particles per m^3.
   - The water temperature is 18 °C.
   - The average velocity gradient in the flocculation basin is $G = 60\ s^{-1}$.
   - We assume that the coagulation process has been optimized so that the particle suspension is completely destabilized: $\alpha = 1.0$.
   - The volumetric flow rate is 0.50 m^3/min, and the volume of the basin is 6.0 m^3.

   Suppose we want to know the number concentration of particles exiting the basin.

   a. Estimate/calculate the floc volume fraction, Ω, for the influent water.

   b. One way to approach this problem is to notice that macroscale flocculation of a monodisperse particle suspension can be treated as a first-order process. Using this approach, estimate/calculate the number concentration of particles in the effluent water.

problem 2 continues →

2. continued

   c. Assuming that the effluent particle suspension is also monodisperse, use your answer from part (b) to estimate/calculate the diameter of the particles in the effluent water. Hint: you can assume that Ω does not change when the particles flocculate, which means that Ω will be the same in the effluent water as it is in the influent water. Based on your estimated diameter, did flocculation succeed in growing the smaller particles into bigger particles?

   d. …but flocculation is actually a second-order process, not a first-order process! Estimate/calculate the second-order flocculation rate coefficient, β, for collisions in this flocculation basin. Hint: use the particle diameter in the flocculation basin (from part c), not the particle diameter entering the flocculation basin.

   e. Write a material balance (mass balance) for particles in the basin, assuming that the flocculation process is a second-order process. Hint: for a completely mixed flow reactor, what is the relationship between the concentration of particles *in* the reactor and the concentration of particles *leaving* the reactor?

   f. Using your equation from part (d), estimate/calculate the concentration of particles exiting the reactor. Does it agree with your estimate from part (b)? What do conclude about treating macroscale flocculation as first-order versus second-order?

3. (35 pts) *This problem is adapted from a problem written by Paul Roberts of Stanford University*. Consider the flocculation of a monodisperse suspension of bacteria in water. The water is 20 °C, the bacterial concentration is 10^{12} bacteria/m^3, and the bacteria can be treated as perfect spheres with volume 10^{-18} m^3. The bacteria are completely destabilized ($\alpha = 1$).

   a. Estimate/calculate the diameter of the bacteria in units of μm.

   b. Consider a single-stage, well-mixed flocculator with $G = 50$ s^{-1}. The flocculator volume is 1000 m^3 and the water flow rate is 10 m^3/min. Estimate/calculate the number concentration of particles exiting the flocculator. For this problem, assume that the bacteria are the only solids present and that macroscale flocculation is the dominant flocculation mechanism for this suspension. Hint: you can estimate the floc volume fraction, Ω, based on the information given.

problem 3 continues→

3. continued

   c. Assume that the flocs leaving the flocculator in part (b) are also spherical. Estimate/calculate the average diameter of the flocs leaving the flocculator, in units of μm. Did the diameter change much from part (a)? In other words, did you make the particles much bigger so that they will settle well during sedimentation?

   d. Now suppose that you add a coagulant, which forms $Al(OH)_3$ or $Fe(OH)_3$ precipitate, such that the volume fraction in the flocculator is $\Omega = 10^{-3}$. Assume that the number concentration entering the flocculator is still 10^{12}, i.e., adding the coagulant did not significantly change the number concentration. (Maybe the coagulant particles coat the surfaces of the bacteria, so the overall number concentration doesn't change.) Assume that these flocs are also spherical. (I kind of question that assumption, but let's use it for now.) Estimate/calculate the diameter of the flocs entering the flocculator.

   e. Estimate/calculate the number concentration of particles exiting the reactor under the conditions of part (d). Did adding the coagulant improve flocculator performance?

   f. Assume that the flocs exiting the reactor in part (d) are also spherical. (Again questionable, but useful for the purposes of this problem.) Estimate/calculate the diameter of the flocs exiting the reactor. Compare this diameter to that of the bacteria. Now did flocculation have a significant effect?

   g. Suppose a colleague told you "if the particle suspension is already destabilized, you don't have to add a coagulant, because the particles are already going to stick together when they collide." Do you agree or disagree? Explain based on your results to parts (a)–(f).

   Note: in this problem, we looked at number concentration and particle diameter. We didn't consider density. Some of the gains in particle diameter are offset by a decrease in particle density, because the flocs get "fluffy" as they grow. But overall, the gains in particle diameter are worth the loss in density – flocculation helps particles settle better!

4. (20 pts) Imagine you are designing a water treatment system for the city of Mudville. The design flow rate is 10 million gallons per day, which is equivalent to 0.438 m^3/s. Mudville's source water contains particles (approximately spherical in shape) of diameter $d = 0.5\ \mu m$ and density $\rho_s = 2.5\ g/cm^3 = 2500\ kg/m^3$. One of your colleagues already designed a rapid-mix system to add alum to the water as a coagulant. Now, you need to design the flocculation basin. You decide to implement flocculation in three stages, i.e., in three completely-mixed flow reactors operated sequentially. This is a pretty typical design for flocculation. In each of these three basins, you aim to reduce the particle number concentration by 85%. The residence time in each of the three basins is 10 minutes. You estimate that the water entering the flocculation basin (i.e., coming from the alum addition) has a concentration of particles $n_I = 3.6\times10^{11}$ particles/m^3.

   a. Calculate the concentration of particles (in number of particles per m^3) exiting the third flocculation basin. How much overall reduction did you achieve in terms of the number concentration?

   b. Calculate the average velocity gradient, *G*, in each of the three basins. Report your answer in units of s^{-1}. Assumed a collision efficiency $\alpha = 0.8$. The floc volume fraction, Ω, is equal to 1.0×10^{-4} in the first basin, 1.6×10^{-4} in the second basin, and 2.6×10^{-4} in the third basin. (Ω increases from one basin to the next because, as the flocs grow in size, they become less tightly packed, so the overall floc volume fraction increases.) Assume that macroscale flocculation is the dominant flocculation mechanism, and that you can treat the suspensions as monodisperse in each of the three basins.

   c. Calculate the power input into each of the three basins and the total power input. You may assume the water is at a temperature of 20 °C. At a rate of 10 cents per kilowatt-hour, how much money will you spend on electricity every day for the mixing of these basins? Does it seem like a reasonable cost?

   d. In problems 2 and 3, I asked you to assume that macroscale flocculation is the dominant flocculation mechanism. Based on your results of problem 1, do you think this is a good assumption? Explain briefly.

5. (20 pts) Answer question 9-12 in the text book. For the differential settling mechanism, assume that all the colliding particles have a density of $1.1\ g/cm^3 = 1100\ kg/m^3$. That is rather a low particle density, but it is appropriate for a "fluffly" floc like $Al(OH)_3$, and besides, it will help you get good agreement with the figure in the text book.

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6. (20 pts) *This problem is from the text book "Principles of Water Treatment" by Howe et al.*

   Assume that addition of ferric sulfate to surface water causes ferric hydroxide to precipitate as uniform spherical particles with an initial diameter of 0.5 μm. For a velocity gradient G = 60 s^{-1} and a temperature of 20 °C, calculate the collision frequency functions for flocculation between these particles and viruses (diameter = 25 nm) due to microscale flocculation, macroscale flocculation, and differential settling. Do the same for *Cryptosporidium* oocysts (diameter = 5 μm). Which mechanism predominates for the flocculation of each type of pathogen with ferric sulfate? For differential settling, assume that flocs and pathogens have a density of 1.1 g/cm^3 = 1100 kg/m^3.