ENV 4001: ENVIRONMENTAL SYSTEMS ENGINEERING

Fall 2021
Problem set #6
Complete by Monday, October 25

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This problem set will not be collected or graded. Your reward for completing this problem set is that it is essential for learning the course material and passing the quizzes and final exam.

1. Look up Sustainable Development Goal #6. Write down the title and the brief description of this goal. Then, look up the *targets* for SDG6 and write down two or three of the targets.

For the remaining problems, 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.

2. 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 concentration by 85%. Notice that this doesn't say reduce *to* 85%, it says reduce *by* 85%.

   [Note: the aim of flocculation isn't actually to reduce particle concentration; it's to make small particles turn into big particles. But when two particles collide and stick together and make a big particle, the number of particles goes down. So if we are reducing the number of particles, then we know the flocculation process is working.]

   The residence time in each of the three basins is 10 minutes. The influent water has a concentration of particles equal to $N_0 = 3.6\times10^{11}$ particles/m^3, and the diameter of the particles is d = 0.5 μm. These particles are approximately spherical in shape and they have a density ρ_s = 2.5 g/cm^3 = 2500 kg/m^3.

   a. Assuming that you successfully meet your target of 85% reduction of particle number concentration in each basin, 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?

problem 2 continues →

2. continued

   b. Calculate the average velocity gradient, G, in each of the three basins. Report your answer in units of s^{-1}. You can get G if you know that the *rate* of particle flocculation (in units of particles per volume per time) is given by

$$R = \frac{4}{\pi}\ \alpha\, G\, \Omega\, N$$

   where N is the number concentration of particles, α is a collision efficiency assumed equal to 0.8, and Ω is the volume concentration of flocs in the basin, which depends on the dose of coagulant. You may assume that 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.) Hint: what type of *kinetics* are indicated by the reaction rate expression given above, i.e., how does the rate R depend upon the number concentration N? What do you know about CMFRs with that type of reaction kinetics at steady state? What would be an equation for N_E/N_I in each basin?

   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?

3. Now that you have your flocculation system, you need to design the sedimentation basins. The basins will be 72 m long, 12 m wide, and 3 m deep. However, based on your design flow rate of 10 million gallons per day, you might need more than one basin operating in parallel.

   a. If you want a residence time of about 3 hr in the sedimentation basins, how many must operate in parallel to treat all of Mudville's water? What will be the actual residence time in the basin?

   b. Imagine that you had *no* coagulation/flocculation step preceding the sedimentation basins. Recall the particles in Mudville's water supply have a diameter d = 0.5 μm, are approximately spherical in shape, and have a density ρ_s = 2.5 g/cm^3 = 2500 kg/m^3. What fractional removal of these particles would you achieve during sedimentation? You may assume the water temperature is 20 °C.

   c. The particles coming out of the three-stage flocculator are bigger but less dense (because, as noted above, the flocs get less tightly packed as they grow). I estimate that the average diameter of the flocs will be 74 μm and the density will be 1.325 g/cm^3 = 1325 kg/m^3. What will be the fractional removal of these flocs in the sedimentation basin?

   d. What do you conclude about putting flocculation upstream of sedimentation? Does it look like a good idea? Why or why not?

4. Next in your treatment plant design, you must design a dual-medium filter for rapid filtration. The plan for the filter is a layer of anthracite and a layer of sand. The hydraulic loading (Q/A) of the filter will be 10 $m^3/(m^2 \cdot hr)$ and the water is 20 °C. Here are the proposed properties of each layer.

Sand: Layer thickness L = 0.75 m
grain size d = 0.70 mm
void fraction ε = 0.45
grain density ρ = 2600 kg/m^3

Anthracite: Layer thickness L = 30 inches
grain size d = 1.6 mm
void fraction ε = 0.50
grain density ρ = 1700 kg/m^3

a. Based on the grain sizes, which medium should be the top layer and which medium should be the bottom? Explain why.

b. Estimate/calculate the head loss through each layer during normal operation at the design hydraulic loading rate. Across which layer does most of the head loss occur? Why?

c. Estimate/calculate the settling rate of each medium after backwashing. Which medium settles faster?

d. Based on your answer to part (c), which medium will end up on the top of the filter, and which on the bottom? Does that agree with your answer to part (a)? If not, then what problem are you going to encounter when you backwash your filters? What could you change to fix this problem?

5. Finally, you must design a disinfection (chlorination) system for the Mudville plant. You must provide a free chlorine residual of at least 1.0 mg/L chlorine in order to protect against contamination in the distribution system. However, you can not exceed a free residual of 2.0 mg/L chlorine, because you are worried about the formation of disinfection by-products.

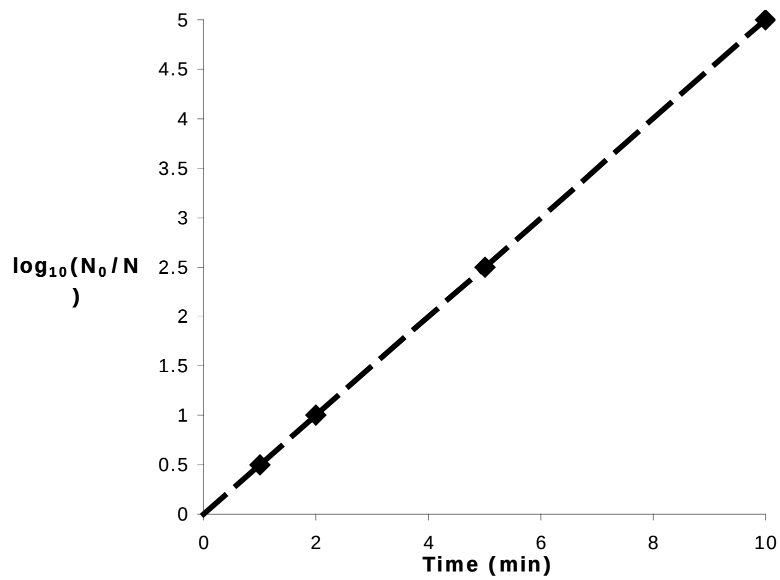
You are given the following data (see next page) for disinfection of *Giardia lamblia*. The data were collected in a batch reactor, using a free residual C = 1.5 mg/L chlorine.

a. From the graph, estimate the first-order rate constant k (in min^{-1}) for both base 10 and base e.

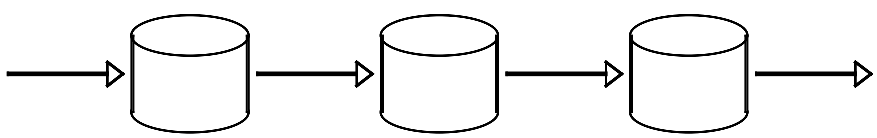
b. Suppose your chlorine contactor is a well-stirred cylindrical tank. The diameter of the tank is 10 m and the depth (height) is also 10 m. What is the average hydraulic residence time, in units of minutes? If the contactor behaves as a CMFR, how much removal of *Giardia* would you get (i.e., what fractional removal)? Hint: be sure to use the proper rate constant k from part (a).

problem 5 continues →

5. continued



c. Now suppose you had three smaller cylindrical tanks. The diameter of each tank is 7 m and the depth (height) of each is also 7 m. Each behaves as an ideal CMFR. You arrange the three tanks in series as shown below. What is the overall removal of *Giardia* that you will achieve?



series configuration

d. Look up the primary standard for disinfection of *Giardia* and report it. Do you meet the standard with one large tank (part b)? Do you meet the standard with three small tanks in series (part c)? Why?

6. Not sure if we will get to softening this year. Every year I hope to get to it, but most years I don't. Check with the instructor to see if this problem is required.

   Imagine that a city (not Mudville, some other city) uses groundwater for its domestic water supply. The water is pretty hard; it contains 78.0 mg/L Ca^{2+}, 24.0 mg/L Mg^{2+}, and 305 mg/L HCO_3^{-}. The pH of the water is 7.8. (These numbers come from an actual groundwater source so they should be quite realistic.)

   a. Calculate the total hardness of the water as mg/L $CaCO_3$.

   b. How much of the total hardness is carbonate hardness? How much is noncarbonate hardness?

   c. If you were building a softening plant to treat this water, would you recommend lime softening or lime-soda softening? Why? Explain briefly.