UNIVERSITY OF OTTAWA
Dept. of Civil Engineering

CVG 3132 Physical/Chemical Unit Operations of Water and Wastewater Treatment
Winter 2011

Assignment #3

Due Thursday March 10th

1. Problems 6.10 from Tchobanoglous and Shroeder
6.10. A reactor that behaves as an ideal PFR is to be used to carry out a BOD removal reaction. The removal rate in the system is given approximately by:

$r_{BODu} = -(k\ BOD_u) / (K+BOD_u\ )$

where
$k = 0.12$ g/m$^3 \cdot$ s
$K= 30$ g/m^3

For a flow of 0.5 m^3/s determine the reactor volume necessary to produce an effluent having 20 g/m^3 *BODu* from the influent which has a *BODu,* of 150 g/m^3

_3. New problem. Design a multi-pass baffled tank chlorine contact for a wastewater treatment plant serving town with a projected population of 30000.
The Recommended Standards for Wastewater Facilities (10-States plus Ontario) include:

- An average daily consumption of 380 L/cap/day.
- The chlorine contact basin has a minimum contact time (or hydraulic residence time = V/Q) of 15 min at the maximum hourly flow and meets the state /provincial effluent standards. For some jurisdiction the minimum detention time may be as high as 45 minutes.
- To allow for maintenance there will duplicate tanks, each should be able to treat 100% of the average flow.
- The peak hourly flow factor will be at least

$$\frac{Q_{peak\ hourly}}{Q_{average}} = \frac{18+\sqrt{P}}{4+\sqrt{P}} \qquad were\ P\ is\ the\ population\ in\ thousands$$

Assume in this case the standard is 2000 faecal coliforms (FC) per liter, and the influent to the basin will have 10^7 FC/L. Based on what you have seen at other plants and the Metcalf & Eddy book you find that:

- at least 3 passes are used
- all the passes generally have the same size
- the length to width ratio for each pass is at least 10:1 and may be as high as 40:1. The tendency is that with a greater number of passes you shorten
- the cross section of the pass have a width to depth ratio ranging from 1:0.5 to 1:2
- assume the sides of the tank will have a freeboard (extra depth) of at least 30 cm to avoid overflow.

Assume that each pass can be simulated as a CSTR with an active volume fraction of 0.85, so a three pass system can be simulated as three equal size CSTR reactors in series. For the selected chlorine dose the kinetics of disinfection are assumed to be

$r_{FC} = -10^{-5} \cdot FC$

TASK:

a) Check if a three pass tank will reduce the concentration sufficiently to meet regulatory requirements. If not expand the number passes to meet the requirement.

b) Design the contact tank, i.e. select the dimensions of the tank, the number of passes, the total hydraulic residence time.

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2. (19 points from the 2003 Final) Tracer test results of the aerated lagoon can be modelled via by the following reactor combination. The kinetics of TOC breakdown within the 1,500 m^3 aeration basin can

$$r = -k \cdot C^{0.888}$$

be described by:

Where C = TOC concentration, g/m^3

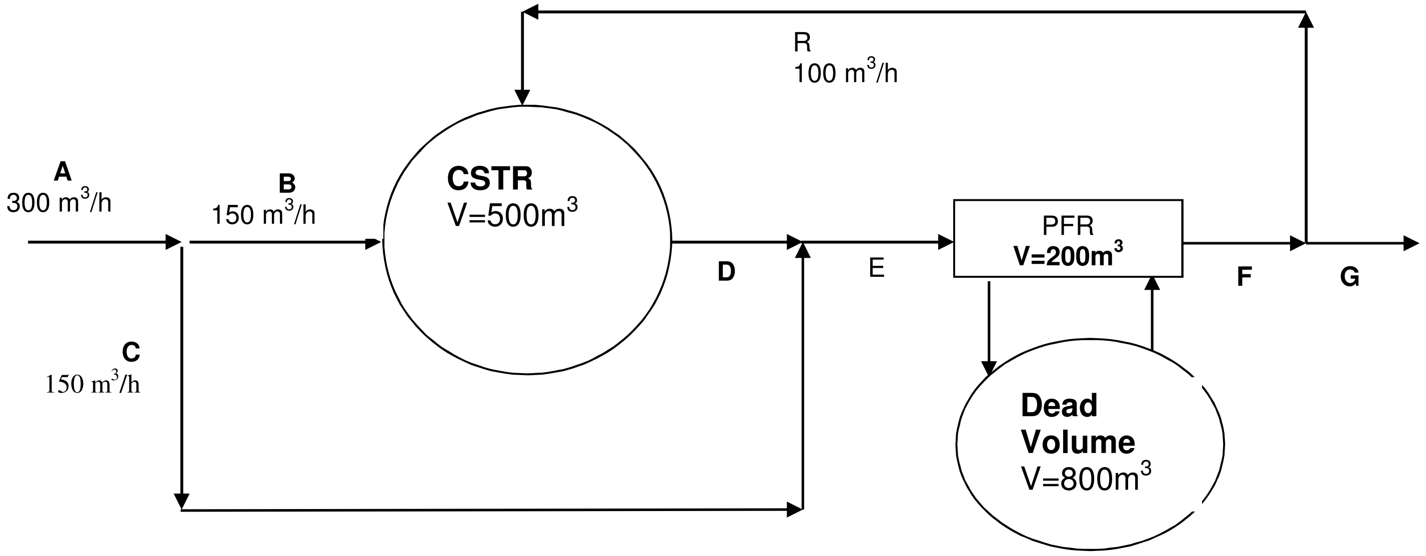
$k = 96\ g^{0.112}/m^{0.336}/d$

The feed TOC concentration is 300 g/m^3.

TASK:

Develop an equation that describes this system's TOC and only has the TOC at D as its unknown. **<u>DO NOT SOLVE</u>**

<u>Show all the equations necessary to arrive at every number you use (i.e., no mass balances in your head even the total (flow) balances) in your calculations, clearly explain every step and state all assumptions.</u>



6.10

PROBLEM

Problem statement - See text page 298

Solution

1. Write steady-state materials balance expression (Eqn. 6.4, p. 278).

$$\frac{d\,BOD_u}{d\,\theta_H} = r_{BOD_u} = -\frac{k\,BOD_u}{K + BOD_u}$$

2. Rearrange materials balance and solve for θ_H.

$$\left(\frac{K + BOD_u}{BOD_u}\right) d\,BOD_u = -k\,d\,\theta_H$$

$$\int_{BOD_{u_i}}^{BOD_u} \left(\frac{K}{BOD_u} + 1\right) d\,BOD_u = k \int_0^{\theta_H} d\,\theta_H$$

$$K \ln \frac{BOD_u}{BOD_{u_i}} + BOD_u - BOD_{u_i} = -k\theta_H$$

3. Substitute given values for BOD_u and BOD_{u_i} and solve for θ_H.

$$(30\ g/m^3 \ln \frac{20\ g/m^3}{150\ g/m^3} + 20\ g/m^3 - 150\ g/m^3 = -0.12\ \frac{g}{m^3}\ \theta_H$$

$$\theta_H = 1587\ s$$

4. Determine reactor volume, $\forall$.

$$\forall = Q\,\theta_H$$

$$= 0.5\ \frac{m^3}{s}\ (1578\ s) = 794\ m^3 \quad \text{ans.}$$

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$$\frac{Q_{peak\ hourly}}{Q_{average}} = \frac{18+\sqrt{P}}{4+\sqrt{P}} \qquad were\ P\ is\ the\ population\ in\ thousands$$

Assume in this case the standard is 2000 faecal coliforms (FC) per liter, and the influent to the basin will have 10^7 FC/L. Based on what you have seen at other plants and the Metcalf & Eddy book you find that:

- at least 3 passes are used
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TASK:

a) Check if a three pass tank will reduce the concentration sufficiently to meet regulatory requirements. If not expand the number passes to meet the requirement.

b) Design the contact tank, i.e. select the dimensions of the tank, the number of passes, the total hydraulic residence time.

We are given the projected population of the town as well as the average per capita daily consumption of water. The product of these two values will be the average discharge through the baffled tank. The projected population is 30000, so in later calculations P=30.

$$Q_{avg} = 380\frac{\frac{L}{capita}}{day} \times 30000\, people = 11400\frac{m^3}{d}$$

The peak hourly flow factor was also provided as a function of the population of the town in thousands. This will allow us to determine the peak hourly design flow.

$$\frac{Q_{peak\ hourly}}{Q_{avg}} = \frac{18+\sqrt{P}}{4+\sqrt{P}} = \frac{18+\sqrt{30}}{4+\sqrt{30}} = 2.477$$

$$Q_{peak\ hourly} = 11400\frac{m^3}{d} \times 2.477 = 28240\frac{m^3}{d} = 1176.7\frac{m^3}{hr} = 19.111\frac{m^3}{min}$$

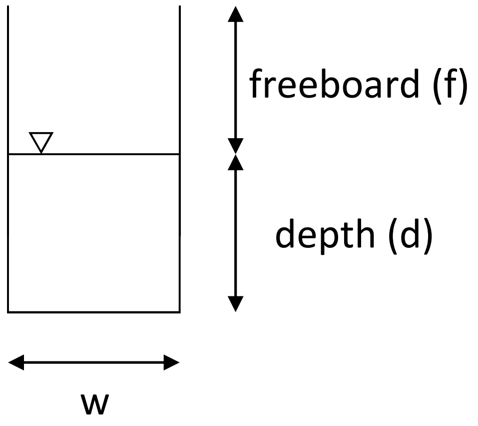
From the specified minimum hydraulic residence time and the design flow, we are able to compute the required volume for the tank.

$$\frac{V}{Q_{peak\ hourly}} \geq \theta_{minimum}$$

$$V \geq 15\, min \times \frac{h}{60\, min} \times \frac{d}{24\, h} \times 28240\frac{m^3}{d}$$

$$V \geq 294.171\, m^3$$

Take 300 m^3 as the initial design volume.



The dimensioning of the tank's features must meet certain criteria. These ratios will help us define the measurements for our design.

$$n = number\ of\ passes$$

$$f = 0.3\ m$$

$$\frac{L}{w} \geq 10$$

$$0.5 \leq \frac{w}{d} \leq 2$$

We can start by expressing each dimension as a function of the width of a pass. Setting this equal to our design volume will give us preliminary dimensions.

$$L \geq 10w$$

$$\text{Setting } \frac{w}{d} = 1 \text{ we find } w = d$$

$$V = (nw)(d)(L) = (3w)(w)(10w) = 300\ m^3$$

$$w = 2.154\ m$$

Therefore

$$L \geq 21.544\ m$$

$$d \approx 2.154\ m$$

$$w \approx 2.154\ m$$

Now we can select the actual dimensions and then check to ensure they will meet the established requirements.

$$L = 25\ m, \qquad w = 2\ m, \qquad d = 2\ m$$

$$\frac{L}{w} = \frac{25\ m}{2\ m} = 12.5 \geq 10$$

$$0.5 \leq \frac{w}{d} \leq 2$$

$$V = (nw)(d)(L) = (3 \cdot 2m)(2\ m)(25\ m) = 300\ m^3$$

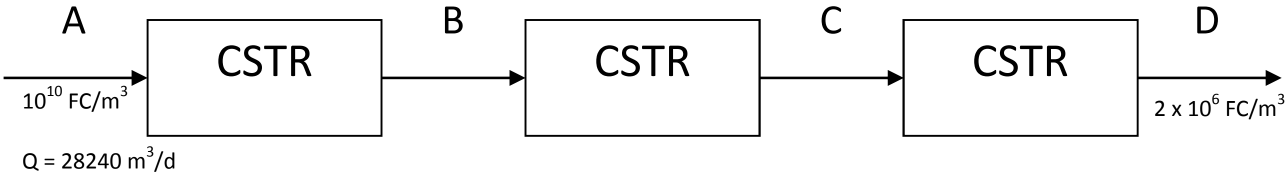
$$\theta = detention\ time = \frac{V}{Q} = \frac{300\ m^3}{19.61 m/min} = 15.3 \min > 15 \min\ O.K.$$

Each pass is to be modeled as a CSTR with an active volume fraction of 0.85. Each reactor will constitute a third of this active volume.

$$V_{active} = 0.85V = 255\ m^3$$

$$V_{CSTR} = \frac{V_{active}}{3} = 85\ m^3$$

$$r_{FC} = -10^{-5} FC$$



We have to verify whether the current number of passes is sufficient to meet the effluent standard for fecal coliforms. All densities are equal to that of water.

Total mass balance around the first CSTR

$$Accumulation = \sum M_{in} - \sum M_{out}$$

$$0 = Q_A \rho_A - Q_B \rho_B$$

$$0 = \left(28240 \frac{m^3}{d}\right) - Q_B$$

$$Q_B = 28240 \frac{m^3}{d}$$

Total mass balance around the second CSTR

$$Accumulation = \sum M_{in} - \sum M_{out}$$

$$0 = Q_B\rho_B - Q_C\rho_C$$

$$0 = \left(28240\frac{m^3}{d}\right) - Q_C$$

$$Q_C = 28240\frac{m^3}{d}$$

Total mass balance around the third CSTR

$$Accumulation = \sum M_{in} - \sum M_{out}$$

$$0 = Q_C\rho_C - Q_D\rho_D$$

$$0 = \left(28240\frac{m^3}{d}\right) - Q_D$$

$$Q_D = 28240\frac{m^3}{d}$$

FC balance around the first CSTR (First pass)

$$Accumulation = Q_A\rho_A - Q_B\rho_B - V_{CSTR}r_{FC}$$

$$0 = Q_AFC_A - Q_BFC_B - V_{CSTR}(10^5FC_B)$$

$$0 = 10^{10}\frac{FC}{m^3} - FC_B - \frac{85\ m^3}{28240\frac{m^3}{d}}(10^5FC_B)$$

$$FC_B = 3.3768 \times 10^7\frac{FC}{m^3}$$

FC analysis for the second CSTR (Second pass)

$$Accumulation = Q_A\rho_A - Q_B\rho_B - V_{CSTR}r_{FC}$$

$$0 = Q_AFC_A - Q_BFC_B - V_{CSTR}(10^5FC_B)$$

$$0 = 3.3768 \times 10^7\frac{FC}{m^3} - FC_B - \frac{85\ m^3}{28240\frac{m^3}{d}}(10^5FC_B)$$

$$FC_B = 1.14027 \times 10^5\frac{FC}{m^3}$$

FC analysis for the Third Pass (Third CSTR)

$$Accumulation = Q_A\rho_A - Q_B\rho_B - V_{CSTR}r_{FC}$$

$$0 = Q_A FC_A - Q_B FC_B - V_{CSTR}(10^5 FC_B)$$

$$0 = 1.14027 \times 10^5 \frac{FC}{m^3} - FC_B - \frac{85\ m^3}{28240\frac{m^3}{d}}(10^5 FC_B)$$

$$FC_B = 385\frac{FC}{m^3}$$

Since the effluent FC is less than 2000FC/L, the disinfection basin performs adequately.

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be described by:

Where C = TOC concentration, g/m^3
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TASK:
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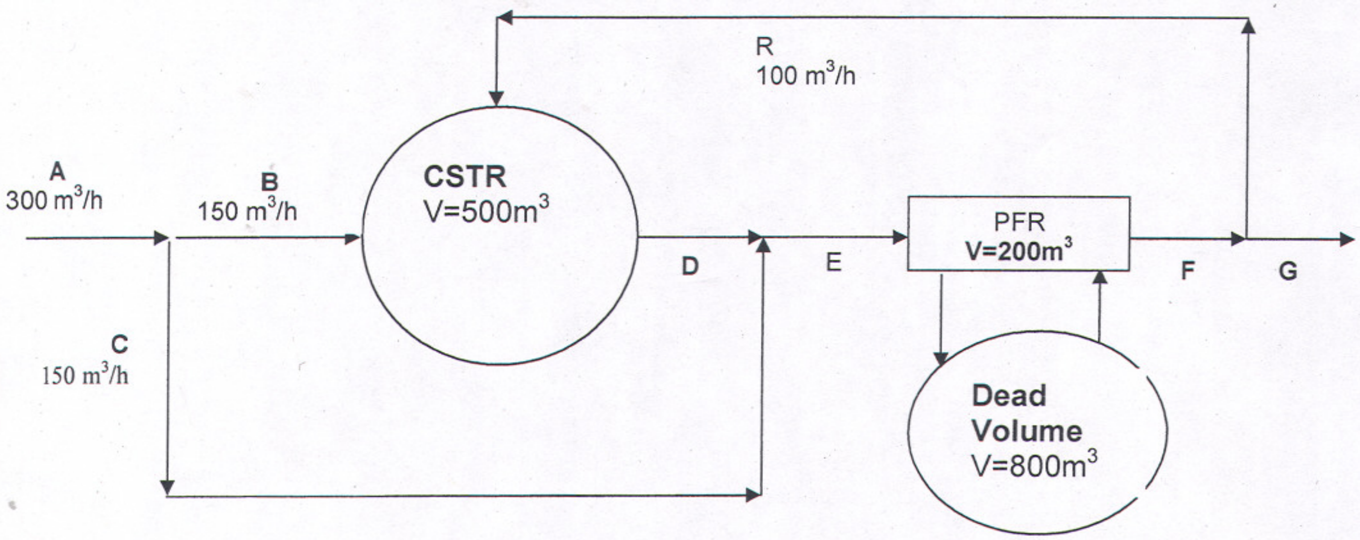

Problem 3

1/3

- Assume steady state conditions prevail
- Assume the density of all the stream = 1000 Kg/m3

Total Mass Balance Around the CSTR

$$\cancelto{0}{Acc}_{S.S.} = Q_B \rho_B + Q_R \rho_R - Q_D \rho_D \qquad ①$$

since $\rho_B = \rho_R = \rho_D = 1000 \text{ kg/m}^3$

$$Q_D = Q_B + Q_R$$
$$= 150 \frac{m^3}{h} + 100 \frac{m^3}{h} = 250 \frac{m^3}{h} = Q_D \qquad ②$$

Total Mass Balance Around the Entire System

$$\cancelto{0}{Acc.}_{SS} = Q_A \rho_A - Q_G \rho_G \qquad ③$$

since $\rho_A = \rho_G = 1000 \text{ kg/m}^3$

$$Q_G = Q_A = 300 \text{ m}^3/h \qquad ④$$

Total Mass Balance Around Mixing point of Streams C&D

$$\cancelto{0}{Acc}_{S.S.} = Q_D \rho_D + Q_C \rho_C - Q_D \rho_D \qquad ⑤$$

since $\rho_D = \rho_C = \rho_D = 1000 \text{ kg/m}^3$

$$Q = Q_D + Q_C$$
$$= 250 \frac{m^3}{hr} + 150 \frac{m^3}{h} = 400 \text{ m}^3/h = Q_E \qquad ⑥$$

Total Mass Balance Around the split of Stream S

$$\cancelto{0}{Acc} = Q_F \rho_F - Q_R \rho_R - Q_G \rho_G \qquad ⑦$$

$$Q_F = Q_R + Q_G$$
$$= 100 \frac{m^3}{h} + 300 \frac{m^3}{h} = Q_F = 400 \frac{m^3}{h} \qquad ⑧$$

Problem 3
2/3

TOC Mass Balance Around Mixing of Streams D & C

$$\cancelto{0\ \text{s.s.}}{\text{Accumulation}} = Q_D \cdot C_D + Q_C \cdot C_C - Q_E \cdot C_E \qquad ⑨$$

Since there is a split $C_B = C_C = C_A = 300\,\text{g/m}^3$

$$0 = \left(250\,\frac{\text{m}^3}{\text{h}} \cdot C_D\right) + \left(150\,\frac{\text{m}^3}{\text{h}} \cdot 300\,\frac{\text{g}}{\text{m}^3}\right) - \left(400\,\frac{\text{m}^3}{\text{h}}\,C_E\right)$$

$\therefore$

$$C_D = -180 + 1.6\,C_E \qquad ⑩$$

or $$C_E = 0.625\,C_D + 112.5 \qquad ⑪$$

TOC Analysis Around the PFR

$$\frac{dc}{d\theta} = -K\,C^{0.888} \qquad ⑫$$

rearrange $$\frac{dc}{C^{0.888}} = C^{-0.112}\,dC = -k\,d\theta$$

Integrate $$\int_{C_E}^{C_F} C^{-0.888}\,dC = -k\int_0^{\theta_{PFR}} d\theta$$

$$\frac{1}{0.112}\,C^{0.112}\Big|_{C_E}^{C_F} = -k\,\theta\Big|_0 \qquad \theta_{PFR} = \frac{V}{Q} = \frac{200\,\text{m}^3}{400\,\text{m/h}} = 0.5\,\text{hr}$$

$$C_F^{0.112} - C_E^{0.112} = -0.112 \cdot 96\,\frac{\text{g}^{0.112}}{\text{m}^{0.336} \cdot \text{d}} \cdot \frac{\text{d}}{24\text{h}} \cdot 0.5\text{h}$$

$$\therefore\ C_F^{0.112} = C_E^{0.112} - 0.224 \qquad ⑬$$

$$C_F = \left(C_E^{0.112} - 0.224\right)^{1/0.112 \;=\; 8.929} \qquad ⑭$$

Problem 3
3/3

and

$$C_E = \left(C_F^{0.112} + 0.224 \right)^{1/0.112} \qquad ⑮$$

And by substituting (1[illegible]) into ⑭

$$C_F = \left(C_E^{0.112} - 0.224 \right)^{1/0.112}$$

$$= \left(\left\{ 0.625\, C_D + 112.5 \right\}^{0.112} - 0.224 \right)^{1/0.112} \qquad ⑯$$

And since stream F splits into G & R

$$C_R = C_G = C_F \qquad ⑰$$

so

$$C_R = \left(\left\{ 0.625\, C_D + 112.5 \right\}^{0.112} - 0.224 \right)^{1/0.112} \qquad ⑱$$

<u>Now analyze the CSTR.</u>

$$\cancel{\frac{d(VC)}{dt}}^{\,0\ \text{SS}} = Q_B C_B + Q_R C_R - Q_D C_D - V \cdot K\, C_D^{0.888} \qquad ⑲$$

$$0 = \left(150\, \frac{m^3}{h} \cdot 300\, \frac{g}{m^3} \right) + \left(100\, \frac{m^3}{hr}\, C_R \right) - \left(250\, \frac{m^3}{h} \cdot C_D \right)$$

$$- 500\, m^3 \cdot 96\, \frac{g^{0.112}}{m^{0.336} \cdot d} \cdot \frac{d}{24 hr} \cdot C_D^{0.888} \qquad ⑳$$

Substitute in ⑱

$$0 = \left(45000\, \frac{g}{h} \right) + \left(100 \cdot \left[\left(\left\{ 0.625\, C_D + 112.5 \right\}^{0.112} - 0.224 \right)^{1/0.112} \right] \right)$$

ANSWER

$$- \left(250 \cdot C_D \right) - \left(2000\, C_D^{0.888} \right)$$