Comparison of CMFR and PFR Steady-State Performance for Pollutant with First-Order Reaction

CENG 340–Introduction to Environmental Engineering

Instructor: Deborah Sills

In Class: October 2, 2013

The ideal CMFR and PFR are fundamentally different, and, thus perform differently. When a parcel of fluid enters a CMFR, it is immediately mixed throughout the reactor. In contrast, when a parcel of fluid enters a PFR it remains separate as it moves through the reactor.

The goal of following problems is to illustrate how this difference affects the performances of CMFRs and PFRs at steady state. In both problems assume that the influent concentration, C_{in}; the flowrate, Q; and the first-order reaction rate constant, k, are known and are the same for both reactors. $Q = 5$ L/s; $k = 0.05\ s^{-1}$.

1. If the volumes of a CMFR and PFR are each 100 L, what is the effluent concentration, C_{out}, as a function of C_{in} for a

   (a) CMFR?

   (b) PFR?

2. If an effluent concentration, C_{out}, equals half of C_{in} ($C_{out} = 0.5 \times C_{in}$), what volume of reactor is required for a

   (a) CMFR?

   (b) PFR?

Mass Balance on Reservoir and Irrigated Farmland

CENG 340–Introduction to Environmental Engineering
Instructor: Deborah Sills
In Class: October 4, 2013

As illustrated in the figure below, a river flows into a reservoir that is being used to irrigate farmland. The river inflow is 30,000 $\frac{m^3}{yr}$ and the salt concentration in the river is 300 $\frac{g}{m^3}$. The reservoir can be modeled as being *completely mixed* with a uniform salt concentration.

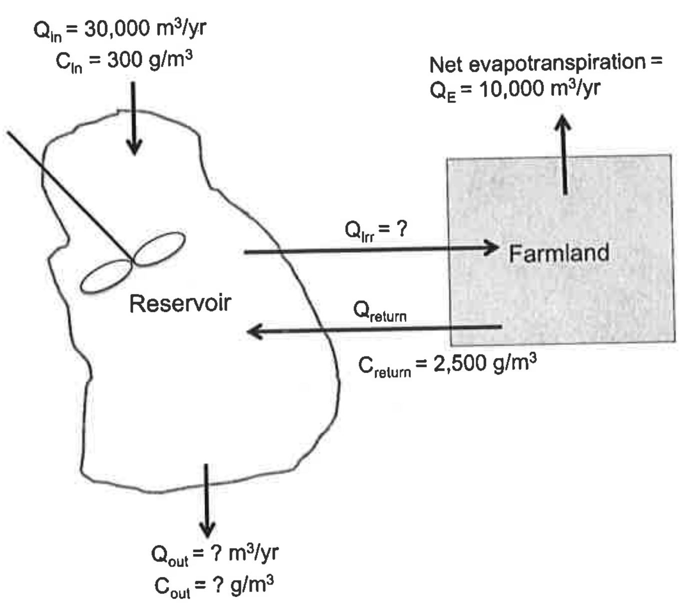
The farmland needs irrigation water to flush salts out of the soil and for use by plants. Water used by plants is lost by evapotranspiration and the net amount of this loss over and above the water input from rainfall, Q_E, equals 10,000 $\frac{m^3}{yr}$.

Salty water from the farm is returned to the reservoir. The salt concentration in the return flow is 2,500 $\frac{g}{m^3}$.

You may assume that the whole system is at steady state with unchanging flows and constant salt concentrations in the river, the agricultural return flow, and the reservoir.

Find:

1. the flow out of the reservoir, Q_{out}.
2. the salt concentration in the reservoir, which is the same as the concentration in the flow out of the reservoir (since the reservoir is completely mixed).
3. the flow rate for the irrigation water, Q_{irr}. Note that this is different from the rate of the return flow.



Coagulation with Alum

CENG 340–Introduction to Environmental Engineering
Instructor: Deborah Sills
In Class: 18 October, 2013

Introduction

You have been asked to design a water treatment facility to meet the following criteria:

- Design capacity = 3.25 MGD
- Source is river water with an initial turbidity of 10 NTU, an alkalinity concentration of 50 mg/L, at 10 ^{0}C and pH = 7.
- Unit operations: coagulation (rapid mix), flocculation, sedimentation, rapid sand filtration, disinfection
- Additional Constraints: units must be sized according to acceptable ranges. Design must accommodate maintenance and repair.

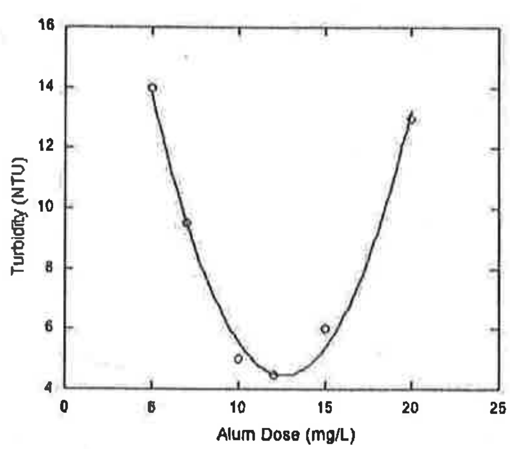
Today, you will design the rapid mix tank used for coagulation.

Background

The purpose of coagulation is to neutralize the charge of small particles (or colloids) in raw (untreated) water, so they can adhere to each other in the subsequent flocculation process. A positively charged *coagulant* is added to water to accomplish coagulation. The most commonly used coagulant is aluminum (Al^{3+}) added as alum $Al_2(SO_4)_3 \bullet 14H_2O$.

Alum Dose:

Estimate the optimal alum dose for turbidity removal based on the following results of a jar test:



Alum

Optimal dose ≅ 12.5 mg/L

Consumption of Alkalinity in units of $CaCO_3$

Estimate the alkalinity consumed at the optimal dosage using the following chemical reaction (Eq. 10.1 on p. 412 of the textbook):

594 g/mole

$$Al_2(SO_4)_3 \bullet 14H_2O + 6\,HCO_3^- \rightarrow 2\,Al(OH)_{3(s)} + 3\,SO_4^{2-} + 6\,CO_2 + 14\,H_2O$$

$$12.5\ \frac{mg\ alum}{L} \times \frac{1\ mole\ alum}{594\ g} \times \frac{6\ eq\ alk}{1\ mol\ alum} \times \frac{100\ g\ CaCO_3}{2\ eq} = 6.3\ mg/L \text{ as } CaCO_3$$

Addition of Alkalinity

If the raw water had an alkalinity of 25 mg/L as calcium carbonate, how much alkalinity (in tons per year) would the plant need to add to the rapid mix tank?

Have 25, need 6.3 for alum addition & coagulation
Since 25 > 6.3, don't need to add alkalinity

Size and Power

Size a rapid-mix tank and determine the power requirements for coagulation? To do so you will need to use *typical values* used in the design of rapid-mix tanks. The following values were taken from Table 10.13 in the textbook:

Table 1: Typical values used in design of a rapid-mixing system (adapted from Mihelcic and Zimmerman).

System Category	RMS Velocity Gradient, $\bar{G}$ (s^{-1})	Retention Time, θ, (s)	$\bar{G}t$ Values
Mechanical Mixing	600–1,000	60–120	5.0×10^3 to 5.0×10^5
In-line Mixing	3,000–5,000	1	5.0×10^3 to 5.0×10^5

Volume

Given: $Q = 3.25\times10^6$ G/day

$T = 10°C \Rightarrow \mu = 1.307\times10^{-3}\ \frac{N\cdot S}{day}$

Pick θ from Table: $\theta = 1$ min

$\forall = \theta \times Q = 3.25\times10^6\ gal/day \times 1\ min \times \frac{1\ day}{24\ h} \times \frac{1\ h}{60\ min} =$

$\forall = 2257$ Gal

Since $\theta = 1-2$ min, say $\forall = 2300$ Gal

Specify FRP tank, and don't need spare.

fiberglass reinforced plastic

Power

$P = \bar{G}^2 \mu V$; choose $\bar{G} = 800\ s^{-1}$

$P = (800\ s^{-1})^2 \times 1.307\times10^{-3}\ \frac{N\cdot S}{m^2} \times 2300\ gal$

$\times\ 3.785\ \frac{L}{gal} \times \frac{1\ m^3}{L}$

$P = 7282\ \frac{N\cdot m}{s} = 7282\ \frac{J}{s} = 7.3\ kW$

(round up)

Specify 2 mixers w/ P = 8 kW, one spare.

Water Treatment Unit Operations—Design Paramters

To be used as part of PSet6
CENG 340–Introduction to Environmental Engineering
Instructor: Deborah Sills
In Class: 21 October, 2013

Introduction

You have been asked to design a water treatment facility to meet the following criteria:

- Design capacity = 3.25 MGD
- Source is river water with an initial turbidity of 10 NTU, an alkalinity concentration of 50 mg/L, at 10 ^{0}C, with dynamic viscosity of $1.307 \times 10^{-3}\ \frac{\mathrm{N}\times\mathrm{s}}{\mathrm{m}^2}$ and pH = 7.
- Unit operations: coagulation (rapid mix), flocculation, sedimentation, rapid sand filtration, disinfection
- Additional constraints: units must be sized according to acceptable ranges. Design must accommodate maintenance and repair.

Approach

1. Identify contaminants to be removed
2. Prepare a block-flow diagram of necessary unit operations, in proper order
3. Complete a conceptual design of each unit operation

Table 1: **Typical values used in design of water treatment systems** (adapted from our textbook).

Unit Operation	Design Basis	Calculate
Coagulation–rapid-mix tank	θ = 1–2 min $\bar{G}$ = 600–1000 s^{-1} Coagulant type	Volume Number of tanks Mixing Power (P) Coagulant dose Alkalinity req'd
Flocculation Tank	θ = 10–30 min $\bar{G}$ = 20–50 s^{-1} (horiz. paddle) $\bar{G}$ = 10–80 s^{-1} (vertical shaft)	Volume Number of tanks Mixing power (P)
Sedimentation tanks	θ = 2–4 h OFR = 700–1400 gpd/ft^2 Weir loading rate = 20,000 gpd/ft	Area Volume Number of tanks Weir length
Filtration (rapid sand)	Hyd. loading rate = 2–6 gpm/ft^2 Depth = 2–6 ft	Area Volume Number of filters
Chlorination	θ_{min} = 15 min (at peak hourly flow) θ_{min} = 30 min (at average hourly flow)	Volume Chlorine dose

Water Treatment Unit Operations—Sedimentation and Filtration

CENG 340–Introduction to Environmental Engineering
Instructor: Deborah Sills
In Class: 23 October, 2013

Sedimentation

Adapted from Davis and Cornwell. The town of San Jose has an existing horizontal-flow sedimentation tank with an overflow rate of 17 $\frac{\mathrm{m}^3}{\mathrm{d} \times \mathrm{m}^2}$. The plant operator wants to remove particles that have settling velocities of 0.1 mm/s, 0.2 mm/s, and 1 mm/s. What percentage of removal should be expected for each particle size in an ideal sedimentation tank.

Filtration

Adapted from Davis and Cornwell. As part of their new treatment plant, the town of San Jose is going to install rapid sand filters after their sedimentation tanks. The design hydraulic loading rate (HLR) to the filter is 200 $\frac{\mathrm{m}^3}{\mathrm{d} \times \mathrm{m}^2}$. How much filter surface area should be provided for the design flow rate of 0.5 $\frac{\mathrm{m}^3}{\mathrm{s}}$?

How large should each filter be if four filters are used?

A number of states require that the design loading rate be met with one filter out of service. Check the HLR for the filter (when one is out of service) to make sure that the HLR is still within the acceptable design range of 2-6 $\frac{\mathrm{gpm}}{\mathrm{ft}^2}$.

Water Treatment Unit Operations—Disinfection

CENG 340–Introduction to Environmental Engineering

Instructor: Deborah Sills

In Class: 25–28 October, 2013

Disinfection Kinetics

A water treatment plant wants to achieve a 3-log removal of *Giardia* cysts with 2 mg/L of chlorine or ozone as a disinfectant.

Calculate the desired percent removal?

Determine the time and volume of reactor required for each disinfectant with $Q = 1$ MGD, $T = 10^0$C, and pH $= 6.5$.

How could you demonstrate that a contact tank has the appropriate retention time for disinfection?

Table 2-3. CT Values for Inactivation of Viruses in Water at 10°C with pH 6.0–9.0

Disinfectant	CT values (in mg-min/L) 2-log Inactivation (99.0%)	3-log Inactivation (99.9%)	4-log Inactivation (99.99%)
Chlorine	3	4	6
Chloramine	643	1,067	1,491
Chlorine Dioxide	4.2	12.8	25.1
Ozone	0.5	0.8	1.0

CT values were obtained from Appendix E (AWWA, 1991).

Table 2-4. CT Values for Inactivation of Giardia Cysts in Water at 10°C with pH 6.0–9.0

Disinfectant	CT values (mg-min/L) 0.5-log Inactivation (68.0%)	1-log Inactivation (90.0%)	1.5-log Inactivation (96.8%)	2-log Inactivation (99.0%)	2.5-log Inactivation (99.7%)	3-log Inactivation (99.9%)
Chlorine[1]	17	35	52	69	87	104
Chloramine	310	615	930	1,230	1,540	1,850
Chlorine Dioxide	4	7.7	12	15	19	23
Ozone	0.23	0.48	0.72	0.95	1.2	1.43

CT values were obtained from Appendix E (AWWA, 1991).

[1] at pH 7.0 and chlorine residual ≤ 0.4 mg/L.

TABLE B-1
CT VALUES* FOR 3-LOG INACTIVATION OF *GIARDIA* CYSTS BY FREE CHLORINE

Chlorine Concentration (mg/L)	Temperature <=0.5°C							Temperature =5°C							Temperature = 10°C						
	pH							pH							pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	137	163	195	237	277	329	390	97	117	139	166	198	236	279	73	88	104	125	149	177	209
0.6	141	168	200	239	286	342	407	100	120	143	171	204	244	291	75	90	107	128	153	183	218
0.8	145	172	205	246	295	354	422	103	122	146	175	210	252	301	78	92	110	131	158	189	226
1.0	148	176	210	253	304	365	437	105	125	149	179	216	260	312	79	94	112	134	162	195	234
1.2	152	180	215	259	313	376	451	107	127	152	183	221	267	320	80	96	114	137	166	200	240
1.4	155	184	221	266	321	387	464	109	130	155	187	227	274	329	82	98	116	140	170	206	247
1.6	157	189	226	273	329	397	477	111	132	158	192	232	281	337	83	99	119	144	174	211	253
1.8	162	193	231	279	338	407	489	114	135	162	196	238	287	345	86	101	122	147	179	215	259
2.0	165	197	236	286	346	417	500	116	138	165	200	243	294	353	87	104	124	150	182	221	265
2.2	169	201	242	297	353	426	511	118	140	169	204	248	300	361	89	105	127	153	186	225	271
2.4	172	205	247	298	361	435	522	120	143	172	209	253	306	368	90	107	129	157	190	230	276
2.6	175	209	252	304	368	444	533	122	146	175	213	258	312	375	92	110	131	160	194	234	281
2.8	178	213	257	310	375	452	543	124	148	178	217	263	318	382	93	111	134	163	197	239	287
3.0	181	217	261	316	382	460	552	126	151	182	221	268	324	389	95	113	137	166	201	243	292

Chlorine Concentration (mg/L)	Temperature = 15°C							Temperature = 20°C							Temperature = 25°C						
	pH							pH							pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	49	59	70	83	99	118	140	36	44	52	62	74	89	105	24	29	35	42	50	59	70
0.6	50	60	72	86	102	122	146	38	45	54	64	77	92	109	25	30	36	43	51	61	73
0.8	52	61	73	88	105	126	151	39	46	55	66	79	95	113	26	31	37	44	53	63	75
1.0	53	63	75	90	108	130	156	39	47	56	67	81	98	117	26	31	37	45	54	65	78
1.2	54	64	76	92	111	134	160	40	48	57	69	83	100	120	27	32	38	46	55	67	80
1.4	55	65	78	94	114	137	165	41	49	58	70	85	103	123	27	33	39	47	57	69	82
1.6	56	66	79	96	116	141	169	42	50	59	72	87	105	126	28	33	40	48	58	70	84
1.8	57	68	81	98	119	144	173	43	51	61	74	89	108	129	29	34	41	49	60	72	86
2.0	58	69	83	100	122	147	177	44	52	62	75	91	110	132	29	35	41	50	61	74	88
2.2	59	70	85	102	124	150	181	44	53	63	77	93	113	135	30	35	42	51	62	75	90
2.4	60	72	86	105	127	153	184	45	54	65	78	95	115	138	30	36	43	52	63	77	92
2.6	61	73	88	107	129	156	188	46	55	66	80	97	117	141	31	37	44	53	65	78	94
2.8	62	74	89	109	132	159	191	47	56	67	81	99	119	143	31	37	45	54	66	80	96
3.0	63	76	91	111	134	162	195	47	57	68	83	101	122	146	32	38	46	55	67	81	97

*Although units did not appear in the original tables, units are min-mg/L.

Theoretical Oxygen Demand

CENG 340–Introduction to Environmental Engineering
Instructor: Deborah Sills
In Class: 1 November, 2013
Problem 5.12 from the Textbook

A waste contains 100 mg/L of acetic acid (CH_3COOH) and 50 mg/L of NH_3-N.

Determine the carbonaceous theoretical oxygen demand (ThOD) of the waste.

Determine the nitrogenous ThOD of the waste.

Determine the total ThOD of the waste.

Will the carbonaceous plus nitrogenous biological oxygen demand (CBOD + NBOD) be higher lower or the same as the ThOD?

Biological Oxygen Demand

CENG 340–Introduction to Environmental Engineering
Instructor: Deborah Sills
In Class: 6 November, 2013

Setting up a BOD Test

You have been asked to set up a series of BOD tests in 300 mL sealed bottles. If the BOD_5 of a waste is 327 mg/L, what sample size should be selected to yield an oxygen consumption of 4.8 mg/L.

Assume that the waste has a k value of 0.12 d^{-1}, and calculate its ultimate BOD (L_0).

Plot the general curves for L(t) and y(t) as shown in your notes and in Fig. 5.23 on p. 195 in the textbook. Identify L(0), L(5), and y(5) (on the graph) and write their values on the plot. Describe the meaning of each term in words.

Sludge (Biomass) Production during Aerobic Wastewater Treatment

Adapted from Example 5.4 in the textbook
CENG 340–Introduction to Environmental Engineering
Instructor: Deborah Sills
In Class: 13 November, 2013

The organic matter presnet in municipal wastewater is removed at a rate of 25 mg BOD_5 per liter per hour in an aerated biological reactor. The aeration tank (or biological treatment reactor) has a volume of 1.5×10^6 L, and the yield coefficient Y equals 0.6 VSS per mg BOD_5

1. What does VSS stand for?

2. How is VSS measured?

3. Calculate the mass of microorganisms produced daily due to the consumption of organic matter by microorganisms in the aeration basin.