

NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER I EXAMINATION 2010-2011

EN3503 / CV4552 – Wastewater Engineering

December 2010

Time Allowed: 2½ hours

INSTRUCTIONS

1. This paper contains **FIVE (5)** questions and comprises **SEVEN (7)** pages.
2. Answer any **FOUR (4)** questions.
3. All questions carry equal marks.
4. An **Appendix of FOUR (4)** pages is attached to the paper.
5. All answers must be written in the answer book provided.
6. This is a Closed-Book Examination.

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1. (a) Two 900 m³ complete-mix reactors are operated in a series. The flow rate through the system of reactors is 400 m³/d. Reaction in the reactor is a second order degradation with reaction coefficient $k = 0.02$ L/(mg day). The inlet concentration into the system is 80 mg/L. Determine the effluent concentration from the second reactor at steady state.

(5 Marks)

- (b) A plug-flow reactor removes substances in a wastewater by a retarded first-order degradation reaction with an exponent $n = 1.4$. The retardation factor $r_t = 0.7$ /day, reaction rate coefficient $k = 0.2$ /day and inlet concentration = 20 mg/L.

- (i) Compare the effluent concentration from the system after 1 day for the case with and that without retardation effects. Determine the effluent concentration if $n = 1$.

- (ii) Discuss the effects of retardation and the reaction exponent n on the reaction.

(10 Marks)

- (c) A plug-flow reactor has a first order BOD removal rate constant of 0.3/day at 20°C and a residence time of 6 days. The system in operation shows dispersion with a dispersion factor of 0.8.

- (i) Determine the effect of dispersion on the effluent concentration.

- (ii) Determine how much longer is the residence time needed to achieve the same amount of BOD removal for the case of 0.8 dispersion versus an ideal plug flow.

(10 Marks)

2. Describe briefly the treatment processes or mechanisms associated with Figures Q2-1 to Q2-7 below.

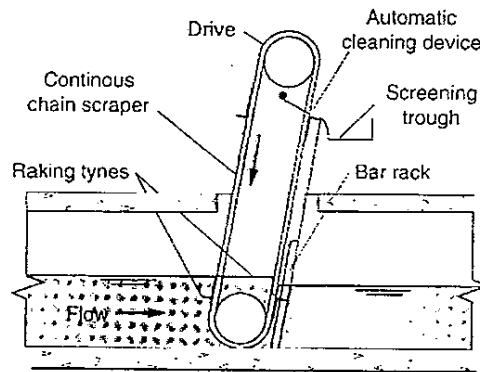


Fig. Q2-1

(3 Marks)

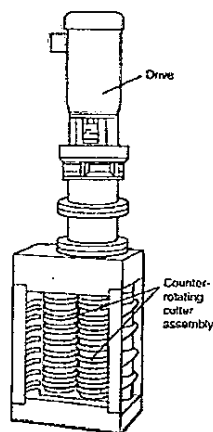


Fig. Q2-2

(2 Marks)

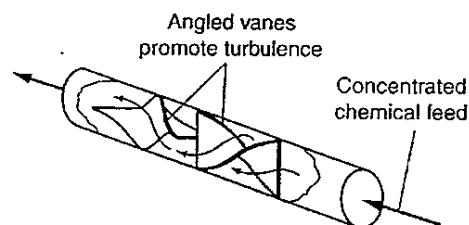


Fig. Q2-3

(2 Marks)

Note: Question No. 2 continues on page 3

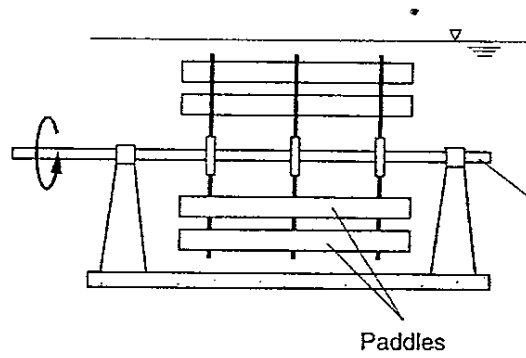


Fig-Q2-4

(2 Marks)

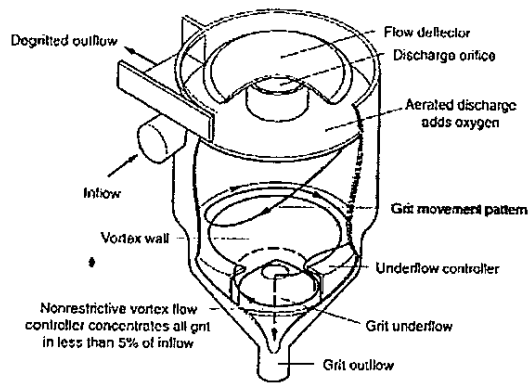


Fig. Q2-5

(4 Marks)

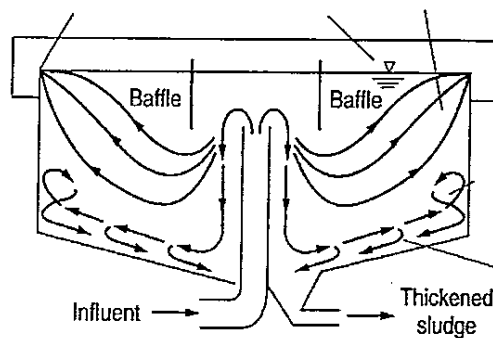


Fig. Q2-6

(6 Marks)

Note: Question No. 2 continues on page 4

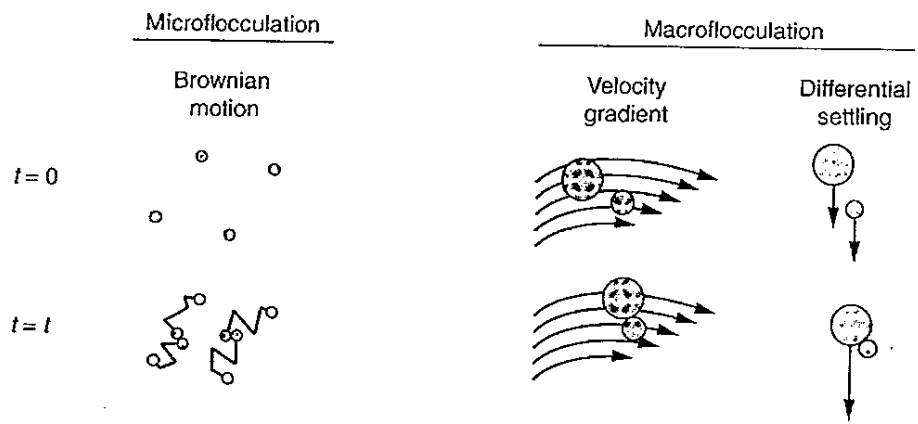


Fig. Q2-7

(6 Marks)

3. (a) Industrial wastewater at a treatment plant has the following characteristics:

bsCOD in the influent = 200 g/m^3
nbVSS in the influent = 60 g/m^3
Influent flow rate = $800 \text{ m}^3/\text{d}$
Biomass concentration in the reactor = $2,200 \text{ g/m}^3$
bsCOD in the reactor = 20 g/m^3
Reactor volume = 100 m^3
Cell debris fraction = 0.2
 $k = 6/\text{day}$
 $K_s = 30 \text{ g/m}^3$
 $k_d = 0.5 \text{ g/g}$
 $Y = 0.3 \text{ g/g}$

Determine the net biomass yield and observed biomass yield.

(6 Marks)

- (b) Explain the difference between net biomass yield and observed biomass yield.

(3 Marks)

- (c) Describe what is contained in volatile suspended solids (VSS).

(3 Marks)

- (d) Between the activated sludge process and trickling filter process, which process would you select for the treatment of wastewater containing substantial amount of suspended solids? Explain the reasons of your selection.

(6 Marks)

- (e) Discuss how sludge solids are traditionally disposed off and what are the innovative ways that can be used to reduce the disposal cost and if possible, generate monetary revenue.

(7 Marks)

4. (a) The average values of the operational parameters of conventional activated sludge plant are listed in Table Q4.

Table Q4

Wastewater flow rate Q ,	7,570 m ³ /d
Wastewater temperature	20°C
Volume of aeration tank	2,260 m ³
Influent BOD ₅	143 mg/L
Influent suspended solids	125 mg/L
Influent total solid	513 mg/L
Effluent total solid	418 mg/L
Effluent TSS	22 mg/L
Effluent BOD	20 mg/L
Returned sludge flow, Q_r ,	3,180 m ³ /d
MLSS	2,600 mg/L
SS in waste sludge	8,900 mg/L
Volume of waste sludge	200 m ³ /d

Calculate the following:

- (i) volumetric loading
- (ii) F/M ratio
- (iii) hydraulic retention time
- (iv) mean cell residence time
- (v) returned activated sludge ratio
- (vi) removal efficiencies for BOD, TSS and total solid

(13 Marks)

- (b) A 9-m diameter by 3-m side wall depth gravity thickener is designed to thicken a primary sludge. The sludge flow is 303 L/min with average solids content of 4.4%. The thickened sludge is withdrawn at 125 L/min with 6.8% solid. The sludge blanket is 1 m thick. The effluent of the thickener has a TSS concentration of 660 mg/L. Determine,

- (i) The sludge detention time.
- (ii) Whether the sludge blanket will increase or decrease in depth under the stated conditions.

(8 Marks)

- (c) Discuss how F/M ratio as an operational parameter for activated sludge process can affect the characteristic of sludge settling.

(4 Marks)

5. (a) A two stage trickling filter system with a design flow rate of 5,680 m³/d and intermediate and secondary settling tanks under the following operational conditions is constructed. The primary effluent (system influent) BOD = 190 mg/L. The design BOD loading rate is 1.5 kg/m³.d. The recycle ratio of both filters is 0.8. Both clarifiers have 20% of the discharged effluent recycled to the influent.
- (i) Determine the volume required for each filter.
 - (ii) Determine the surface area of the filter. Assume that the side water depth is 4 m.
 - (iii) Calculate the hydraulic retention time (HRT). Assume 4 m deep filters with an area of 90 m².
 - (iv) Determine the size for the intermediate clarifier. Assume hydraulic loading rate (HLR) = 41 m³/m².d and a minimum depth of 3 m.
 - (v) Determine the size of the secondary clarifier. Assume HLR = 31 m³/m².d and the same minimum depth as the intermediate clarifier.
- (15 Marks)
- (b) A complete-mix aerated lagoon system has the following operational and kinetic parameters as listed in Table Q5.

Table Q5

Parameters		Kinetic coefficients	
Wastewater flow rate	3,000 m ³ /d	K	5 d ⁻¹
Influent soluble BOD ₅	180 mg/L	K _s	60 mg/L BOD
Effluent soluble BOD ₅	20 mg/L	Y	0.6 mg/mg
Soluble BOD ₅ first order k ₂₀	2.4 d ⁻¹	K _d	0.06 d ⁻¹
Influent TSS (not biodegraded)	190 mg/L	Design depth of lagoon	3 m
Final effluent TSS	22 mg/L	Design HRT	5 d
MLVSS/MLSS	0.8	Detention in settling tank	2 d
Temperature coefficient	1.07	Wastewater temperature	15°C
Summer mean air temperature	26.5°C	Winter mean air temperature	9°C

- (i) Determine the surface area of the lagoon.
- (ii) Calculate the wastewater temperature in the summer and winter.
- (iii) Calculate the first order BOD removal rate constant for the summer and winter.
- (iv) Calculate the effluent BOD₅ in the summer and winter.
- (v) Calculate the TSS in the lagoon effluent before settling.

(10 Marks)

END OF PAPER

Appendix

$$\frac{C}{C_0} = \frac{4a \exp\left(\frac{1}{2d}\right)}{(1+a)^2 \exp\left(\frac{a}{2d}\right) - (1-a)^2 \exp\left(-\frac{a}{2d}\right)}$$

$$a = \sqrt{1 + 4k\tau d}$$

$$\frac{C}{C_0} = e^{-kt}$$

$$C = C_0 \exp\left[-\frac{k}{r_i} \ln(1 + r_i t)\right] \quad \text{for } n = 1$$

$$C = C_0 \exp\left\{-\frac{k}{r_i(n-1)} \left[1 - \frac{1}{(1 + r_i t)^{n-1}}\right]\right\} \quad \text{for } n \neq 1$$

$$r_{su} = -\frac{kXS}{K_S + S}$$

$$r_g = -Yr_{su} - k_d X$$

$$r_{X_T, VSS} = -Yr_{su} - k_d X + f_d(k_d)X + \frac{QX_{o,i}}{V}$$

$$\frac{L_e}{L_o} = \frac{1}{1 + KXt}$$

where L_e = BOD after treatment (mg/l)
 L_o = BOD before treatment (mg/l)
 X = MLVSS (mg/L)
 t = aeration time
 k = BOD removal rate constant

$$(T_i - T_w) = \frac{(T_w - T_a) fA}{Q}$$

where T_i = influent waste temperature, °C
 T_w = lagoon water temperature, °C
 T_a = ambient air temperature, °C
 f = proportionality factor = 0.5
 A = surface area, m²
 Q = flow rate, m³/d

or

$$\frac{d}{t} = 0.5 \frac{(T_w - T_a)}{(T_i - T_w)}$$

where d = depth, m
 t = detention time, days

$$\frac{S}{S_o} = \frac{4a \exp(1/2d)}{(1+a)^2 \exp(a/2d) - (1-a)^2 \exp(-a/2d)}$$

where S = effluent substrate concentration
 S_o = influent substrate concentration
 $a = \sqrt{1 + 4kdt}$
 d = dispersion factor = $D/\mu L$
 D = axial-dispersion coefficient, sq ft/hr
 μ = fluid velocity, ft/hr
 L = characteristic length, ft
 k = first-order reaction constant
 t = detention time.

a. US National Research Council (NRC) formula

The formula for a single-stage or first-stage units is:

$$E_1 = \frac{100}{1 + 0.443 \left(\frac{W}{VF} \right)^{1/2}}$$

where E_1 = % BOD removal efficiency through the first filter and clarifier, %
 V = volume of filter media; m³
 W = BOD loading to filter, kg/day (not including recycle)
 F = recirculation factor

$$\frac{1 + R}{(1 + 0.1R)^2}$$

R=recirculation ratio=recirculated flow/plant influent flow

For the second-stage filter

$$E_2 = \frac{100}{1 + \frac{0.443}{1 - E_1} \left(\frac{W'}{VF}\right)^{1/2}}$$

where E_1 = fraction of BOD removal in the first stage.

E_2 = % BOD removal efficiency through the 2nd stage filter and clarifier

W' = BOD loading to the second-stage filter not including recycle, kg/day
 $= W(1-E_1)$

The effect of the wastewater temperature on stone-filled trickling filter efficiency may be expressed as follows:

$$E = E_{20} \times 1.035^{T-20}$$

First order kinetic:

$$K_{T1} = K_{T2}(1.07)^{T1-T2}$$

K are first order kinetic constant, K_{T1} at temperature T1 and K_{T2} at T2.

T is Temperature

$$\frac{A}{S} = \frac{1.3s_a(fp-1)}{S_s} \text{ (without recycle)}$$

where A/S = air solids ratio, mL (air)/mg (solids)

s_a = air solubility, mL/L

f = fraction of air dissolved at pressure p,

P = pressure, atm, absolute

$$P = \frac{p_p + 101.35}{101.35} \text{ (SI units)}$$

p_p = gage pressure, kPa

s_s = sludge solids, mg/L

The concentration equation for a system with only pressurized recycle is

$$\frac{A}{S} = \frac{1.3s_a(fp-1)R}{S_s Q}$$

where R = pressurized recycle, m³/d

Q = mixed liquor flow, m³/d

$$\frac{S}{S_0} = \frac{1}{1 + K\theta}$$

where S = effluent BOD₅ concentration, (mg/L)

S_0 = Influent BOD₅ concentration, (mg/l)

θ = total hydraulic retention time, d

k=overall first order BOD₅ removal rate constant, d⁻¹

Appendix to EN3503 / CV4552

$$S = K_s(1 + \theta K_d) / (\theta(YK - K_d) - 1)$$

$$X = Y(S_0 - S) / (1 + K_d\theta)$$

where K_s = half saturation constant

K_d = decay constant, d^{-1}

S_0 =, mass concentration of substrate in influent, mg/L

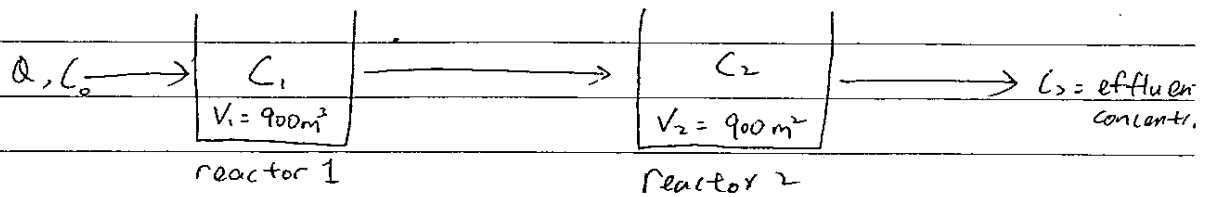
S = substrate concentration in effluent, mg/L

θ = hydraulic retention time, d

Y = maximum yield coefficient, growth mg/mg.

X = microorganism concentration in tank, mg/L

1(a)



Applying mass balance eq to reactor 1,

$$\frac{dC_1}{dt} V_1 = Q C_0 - Q C_1 + r V$$

∴ steady state, $\frac{dC_1}{dt} = 0$ second order rxn, $r = -k C_1^2$

$$\therefore Q C_0 - Q C_1 - k C_1^2 V = 0$$

$$k C_1^2 V + Q C_1 - Q C_0 = 0$$

$$C_1 = \frac{-Q \pm \sqrt{Q^2 + 4kVQC_0}}{2kV}$$

$$= \frac{-400 \pm \sqrt{400^2 + 4(0.02)(900)(400)(80)}}{2(0.02)(900)}$$

$$= 32.49 \text{ (mg/L)}$$

$$\text{Similarly, } C_2 = \frac{-400 \pm \sqrt{400^2 + 4(0.02)(900)(400)(32.49)}}{2(0.02)(900)}$$

$$= 17.96 \text{ (mg/L)}$$

1(b) Given $v_e = 0.7/\text{day}$ $k = 0.2/\text{day}$ $C_0 = 20 \text{ mg/L}$ $n = 1.4$ $T = 1 \text{ day}$

(i)

with retardation (with $n = 1.4$)

$$C = C_0 \exp \left\{ \frac{k}{-v_e(n-1)} \left[1 - \frac{1}{(1+v_e t)^{n-1}} \right] \right\}$$

$$= 20 \exp \left\{ \frac{0.2}{0.7(0.4)} \left[1 - \frac{1}{(1+0.7 \times 1)^{0.4}} \right] \right\}$$

$$= 17.47 \text{ (mg/L)}$$



1(b) continued.

(i) with $n=1$

$$C = C_0 \exp \left[-\frac{k}{r_t} \ln (1 + r_t t) \right]$$
$$= 20 \exp \left[-\frac{0.2}{0.7} \ln (1 + 0.7 \times 1) \right]$$
$$= 17.17 \text{ (mg/L)}$$

without retardation effect,

$$C = C_0 e^{-kt}$$
$$= 20 e^{-0.2(1)}$$
$$= 16.37 \text{ (mg/L)}$$

ii) Without retardation effect, the removal efficiency of the reactor is higher. The higher the 'n' value, the greater the retardation effect, hence the lower the removal efficiency.

1(c) Given residence time = 6 days, removal rate constant = 0.3/day, dispersion factor = 0.8

(i) $a = \sqrt{1 + 4kTd}$

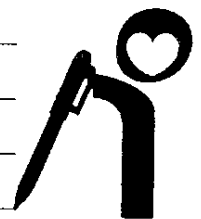
$$= \sqrt{1 + 4(0.3)(6)(0.8)}$$
$$= 2.6$$

$$\frac{C}{C_0} = \frac{4a \exp\left(\frac{1}{2d}\right)}{(1+a)^2 \exp\left(\frac{a}{2d}\right) - (1-a)^2 \exp\left(-\frac{a}{2d}\right)}$$
$$= \frac{4(2.6) \exp\left(\frac{1}{2 \times 0.8}\right)}{(1+2.6)^2 \exp\left(\frac{2.6}{2 \times 0.8}\right) - (1-2.6)^2 \exp\left(-\frac{2.6}{2 \times 0.8}\right)}$$
$$= \frac{19.43}{65.82 - 0.504}$$
$$= 0.297$$

BOD removal = $1 - 0.297 \approx 0.7 \approx 70\%$

without dispersion, $\frac{C}{C_0} = e^{-0.3(6)} = 0.165$

\Rightarrow BOD removal = $1 - 0.165 = 0.835 = 83.5\%$



1(c) To achieve same removal efficiency with ideal plug flow,

$$\text{i.e. } \frac{C}{C_0} = 0.165$$

$d = 0.8$, $\frac{C}{C_0} = 0.165 \Rightarrow$ refer to Wehner & Wilhelm eq.,
 $KT \approx 2.5$.

\therefore residence Time required = $\frac{2.5}{0.3} \approx 8.3$ days.

2) Fig Q2-1

- Oversized (or larger) material which may destroy the remaining units of treatment process is barred from entering by screening. The material collected by screens is cleaned off mechanically by this apparatus.

Fig Q2-2

- A macerator is a slow-speed grinder that grind material in the wastewater to ensure only small and fairly even sized material entering wastewater treatment plant.

Fig Q2-3.

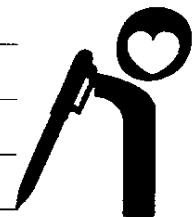
- Mixing is achieved by turbulence created by the angled vanes. Sufficient mixing is required for coagulation process.

Fig Q2-4.

- It's a paddle mixer for flocculation. The mixer induces the coagulated particles to collide and form aggregates.

Fig Q2-5

- It is a grit chamber which is used for grit removal. The flow travels in a spiral pattern, generating centrifugal forces that separate the grit material from organic matter in the wastewater.



2) Fig Q2-6

- It is a circular sedimentation tank. Sedimentation is a process to separate solid/suspended particle from the wastewater. The clarified water is collected through an effluent weir near the top while the thickened sludge is collected from the bottom.

Fig Q2-7.

- Microfloculation (also known as perikinetic flocculation) is significant for particles of diameter from 0.001 to 1 μm . It is essentially aggregation of particles due to Brownian motion (diffusion).

- Macrofloculation is significant for particles with diameters greater than 1 μm . It is essentially aggregation of particles due to velocity gradient or differential settling velocities.

$$3) (a) r_{su} = \frac{-kXS}{K_s + S}$$

$$= \frac{-6(2200)(20)}{30 + 20}$$

$$= -5280$$

$$r_g = -Yr_{su} - k_d X$$

$$= -0.3(-5280) - 0.5(2200)$$

$$= 484$$

Net biomass yield, $Y_{bio} = \frac{-r_g}{r_{su}}$

$$= \frac{-484}{-5280} = 0.091 \text{ (g VSS / g bCOD)}$$

$$r_{XT, VSS} = -Yr_{su} - k_d X + f_d(k_d)X + QX_{0,i}$$

$$= 484 + 0.2(0.5)(2200) + \frac{800(60)}{100}$$

$$= 1184$$

Observed biomass yield, $Y_{obs} = \frac{-r_{XT, VSS}}{r_{su}} = \frac{-1184}{-5280} = 0.22$ (g VSS/g bCOD)



5) (b) Net biomass yield - biomass growth vs substrate consumption

$$Y_{bio} = - \frac{r_g}{r_{su}}$$

Observed Yield - solids production vs substrate consumption

$$Y_{obs} = - \frac{r_{xT, VSS}}{r_{su}}$$

(c) VSS contains active cell biomass, cell debris from decay of cells (non-biodegradable) and non-biodegradable VSS in the influent wastewater.

(d) I would select activated sludge process. The substantial amount of suspended solids may clog the spraying nozzle for the trickling filter process, making it a less favourable option. The too heavy suspended solids content may also slough off the working biofilm in the biofilter, rendering an incomplete treatment.

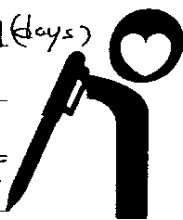
(e) Traditionally, sludge solids are disposed off to the sea, or made into fertiliser & compost. Recently, it was suggested to be made into horticultural aggregate (and generate monetary value).

$$4) (a)(i) \text{Volumetric loading} = \frac{BOD \times Q}{V} = \frac{143 \times 7570 \times 10^{-3}}{2260} \\ = 0.479 \text{ Kg/m}^3 \cdot \text{d}$$

$$(ii) \frac{F}{M} \text{ ratio} = \frac{BOD \times Q}{MLVSS \times V} = \frac{143 \times 7570 \times 10^{-3}}{0.8 \times 2600 \times 2260 \times 10^{-3}} \\ = 0.23$$

$$(iii) \text{Hydraulic detention time} = \frac{V}{Q} = \frac{2260}{7570} = 0.299 \text{ (days)}$$

$$(iv) \text{Mean cell residence time} = \frac{V \times X}{Q_w \times X_r} = \frac{2620 \times 2600 \times 0.8}{200 \times 8900 \times 0.8} \\ = 3.827 \text{ (days)}$$



$$\begin{aligned}
 4)(OXV) \text{ Return activated sludge ratio} &= \frac{X}{X_r - X} \\
 &= \frac{2600}{8900 - 2600} \times 100 \\
 &= 41.27\%
 \end{aligned}$$

(Vi) Removal efficiency:

$$① \text{ BOD} \Rightarrow \frac{143 - 20}{143} \times 100 = 86\%$$

$$② \text{ TSS} \Rightarrow \frac{125 - 22}{125} \times 100 = 82.4\%$$

$$③ \text{ Total solid} \Rightarrow \frac{513 - 418}{513} \times 100 = 18.52\%$$

$$\begin{aligned}
 4) (b) (i) \text{ The sludge detention time} &= \frac{V}{Q} \\
 &= \frac{\pi (4.5)^2 (3)}{303 \times 10^{-3}} \\
 &= 629.87 \text{ (mins)}
 \end{aligned}$$

(ii)* Assume the % given is by volume

$$\begin{aligned}
 \text{Sludge solid in} &= 303 \text{ L/min} \times 4.4\% \\
 &= 13.332 \text{ L/min}
 \end{aligned}$$

$$\begin{aligned}
 \text{Sludge solid out} &= 125 \text{ L/min} \times 6.8\% \\
 &= 8.5 \text{ L/min}
 \end{aligned}$$

Since in > out, the sludge blanket will increase.

C) At high F/M ratio, microorganisms are in log growth phase, which is characterized by excess food and maximum rate of metabolism, however the settling is 'bad' as microorganisms remain in dispersed state. At low F/M ratio, the settling characteristic is good, but the metabolism rate is low. Hence, a compromise should be chosen between high & low F/M ratio.



$$3 (a) (i) \text{ volume} = \frac{170 \times 10^6 \times 3.680}{1.5}$$

$$= 719.47 \text{ m}^3$$

$$\approx 720 \text{ m}^3$$

$$(ii) \text{ The surface area} = \frac{V}{\text{depth}} = \frac{720}{4} = 180 \text{ m}^2$$

$$(iii) \text{ Given } 4 \text{ m depth, } 90 \text{ m}^2 \text{ surface area} \Rightarrow \text{Volume} = 90 \times 4 = 360 \text{ m}^3$$

$$\text{HRT} = \frac{V}{Q} = \frac{360}{5680} = 0.063 \text{ (days)}$$

$$(iv) \text{ surface area for clarifier} = \frac{Q}{\text{HLR}} = \frac{5680}{41} = 138.53 \text{ m}^2$$

$$\text{Volume} = \text{surface area} \times \text{depth} = 138.53 \times 3 = 415.6 \text{ m}^3 \approx 420 \text{ m}^3$$

$$(v) \text{ surface area} = \frac{Q}{\text{HLR}} = \frac{5680}{31} = 183.22 \text{ m}^2$$

$$\text{Volume} = \text{area} \times \text{depth} = 183.22 \times 3 = 549.6 \approx 550 \text{ m}^3$$

$$5 (b) (i) \text{ volume} = \text{HRT} \times Q = 3000 \times 5 = 15000 \text{ m}^3$$

$$\text{surface area} = \frac{V}{d} = \frac{15000}{3} = 5000 \text{ m}^2$$

$$(ii) \text{ summer: } \frac{d}{t} = 0.5 \frac{(T_w - T_a)}{(T_i - T_w)} \Rightarrow \frac{3}{5} = 0.5 \frac{(T_w - 26.5)}{(15 - T_w)} \Rightarrow T_w = 20.22^\circ \text{C}$$

$$\text{winter: } \frac{3}{5} = 0.5 \frac{(T_w - 9)}{(15 - T_w)} \Rightarrow T_w = 12.27^\circ \text{C}$$

$$(iii) k_{\text{summer}} = k_{20} \theta^{T_w - 20} = 2.4 \times 1.07^{(20.22 - 20)} = 2.44$$

$$k_{\text{winter}} = 2.4 \times 1.07^{(12.27 - 20)} = 1.42$$

(iv) In summer,

$$S = \frac{S_0}{1 + kt} = \frac{180}{1 + (2.44)(5)} = 13.6 \text{ (mg/L)}$$

In winter,

$$S = \frac{180}{1 + (1.42)(5)} = 22.22 \text{ (mg/L)}$$

$$(v) \text{ TSS} = 190 - 22 = 168 \text{ (mg/L)}$$

