5
PHYSICAL UNIT OPERATIONS

PROBLEM 5-1

Problem Statement - See text, page 448

Solution

Following values were given in the problem statement:

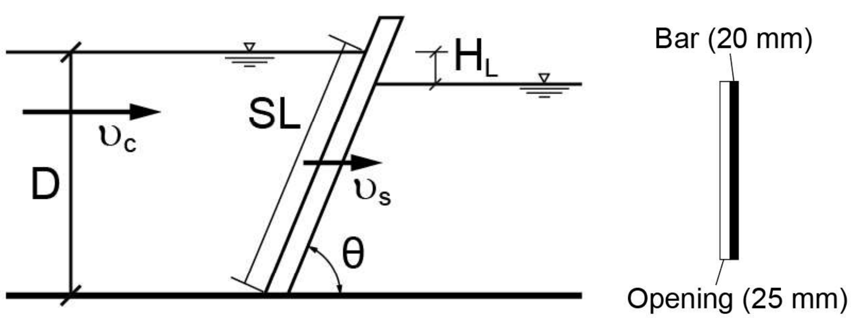
υ_c = channel velocity = 1 m/s

BW = bar width = 20 mm

CS = clear spacing = 25 mm

Θ = screen angle = 50°, 55°, 60°

Definition Sketch:



H_L = headloss

D = water depth

SL = slot length

υ_s = velocity through the screen

Following steps are taken to find the headloss, H_L. and velocity, υ_s

1. Find velocity through screen, υ_s, for one screen opening.

   Water occupying the cross section area of one bar and one opening space, Q, will approach the screen, and pass through the area of one opening. Approaching velocity can be expressed as:

$$\upsilon_c = 1\,\text{m/s} = \frac{\text{(Volume of water passing one opening)}}{\text{(Area for one screen bar + one opening)}} = \frac{Q}{(BW + CS)(D)}$$

Through the opening, velocity through the slot can be written as:

$$\upsilon_s = \frac{Q}{(CS)(SL)}$$

Solve the two equations for Q to yield:

$\upsilon_c (BW + CS) D = Q = \upsilon_s (CS)(SL)$, or

$$\upsilon_s = \frac{(BW + CS)D}{(CS)(SL)} \upsilon_c$$

Given BW = 25 mm, CS = 20 mm

$$\upsilon_s = \frac{(20 + 25)D}{(25)SL} \upsilon_c$$

Where $SL = \frac{D}{(SM)\theta}$

$$\upsilon_s = \frac{45\,D}{(25)\left[\left(\frac{D}{\sin\theta}\right)\right]} \upsilon_c$$

$\upsilon_s = \frac{45 \sin\theta}{25} \upsilon_c$, and υ_c = 1.0 m/s

For the θ = 50, 55 and 60°, υ_s is calculated (see the following table). As a reference, the result for θ = 90° is also shown.

	θ,°	υ_s, m/s
A	50	1.38
B	55	1.47
C	60	1.56
D	90	1.80

2. Find headloss through screen:

From Eq. 5-1 (page 317),

$$H_L = \frac{1}{C}\left(\frac{\upsilon_s^2 - \upsilon_c^2}{2g}\right)$$

Where C = discharge coefficient (from table) = 0.7 (assumed)

$$H_L = \frac{1}{0.7}\left(\frac{\upsilon_s^2 - (1.0)^2}{(2)(9.81)}\right)$$

The results are summarized below.

	Θ,°	υ_s, m/s	H_L, m
A	50	1.38	0.066
B	55	1.47	0.084
C	60	1.56	0.10
D	90	1.80	0.16

PROBLEM 5-2

Problem Statement - See text, page 448

Solution

Following values were given in the problem statement:

Q = flow = 40,000 m^3/day = 0.463 m^3/s (a)

υ_c = upstream channel velocity > 0.4 m/s

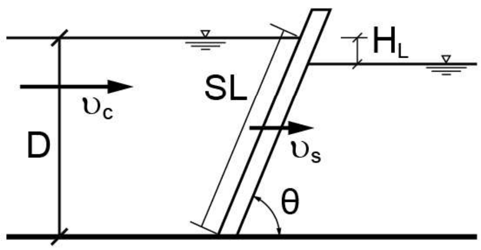
BW = bar width = 12 mm = 0.012 m

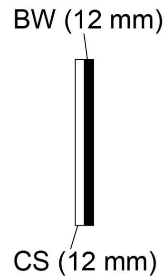
CS = clear spacing = 12 mm = 0.012 m

θ = screen angle = 75°

1. Find H_L = headloss through clean screen and through 50% clogged screen.

<u>Design Sketch</u>





D = water depth

SL = screen length

a. Find channel dimensions
Assume υ_c = 0.4 m/s

$$Q = \upsilon_c A$$

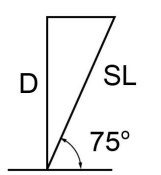
$$A = \frac{Q}{\upsilon_c} = \frac{(0.463\ m^3/s)}{(0.4\ m/s)} = 1.1574\ m^2$$

Where A = area of the channel

Assume channel width (w) upstream of the screen = 0.5 m

$$D = \frac{1.1574\ m^2}{0.5\ m} = 2.3148\ m$$

b. Find screen length (SL)



$$\sin 75° = \frac{D}{SL}$$

$$SL = \frac{D}{\sin 75°} = \frac{2.3148\ m}{0.9659} = 2.3965\ m$$

c. Find velocity through screen (υ_s) for clean screen
The bars are 12 mm wide and the clear spacing between bars is 12 mm. Therefore, the area of flow through the screen, A_s, is 50% of the screen area.

$$A_s = (SL)(w)(0.50) = (2.3965\text{m})(0.50\text{m})(0.50) = 0.5991\text{m}^2$$

$$\upsilon_s = \frac{(0.463\ \text{m}^3/\text{s})}{0.5991\ \text{m}^2} = 0.7727\ \text{m/s}$$

d. Find headloss through clean screen

Equation 5-1 (page 317):

$$H_L = \frac{1}{C}\left(\frac{\upsilon_s^2 - \upsilon_C^2}{2g}\right)$$

Assume C (for a clean screen) = 0.70

$$H_L = \frac{1}{0.7}\left[\frac{(0.7727\ \text{m/s})^2 - (0.4\ \text{m/s})^2}{(2)(9.81\,\text{m/s}^2)}\right] = 0.0318\text{m}$$

e. Find headloss through screen that is 50% clogged
Equation 5-1 (page 317)

$$H_L = \frac{1}{C}\left(\frac{\upsilon_s^2 - \upsilon_C^2}{2g}\right)$$

Assume C for a clogged screen = 0.60

If the screen is 50% clogged, then the velocity will double. Therefore,

$$V_s = 2(0.7727\ \text{m/s}) = 1.5455\ \text{m/s}$$

$$H_L = \frac{1}{0.6}\left[\frac{(1.5455\ \text{m/s})^2 - (0.4\ \text{m/s})^2}{(2)(9.81\,\text{m/s}^2)}\right] = 0.1893\text{m}$$

PROBLEM 5-3

Problem Statement - See text, page 448

Solution

1. Compute the Reynolds number (N_R) using Eq. (5-11) in p337.

$$N_R = \frac{D^2 n\rho}{\mu}$$

Required data:

D = 3 m

$n = 30$ r/min = 0.5 r/s

$\rho = 995.7\ kg/m^3$ (Table C-1)

$\mu = 0.798 \times 10^{-3}\ N{\bullet}s/m^2$ (Table C-1)

$$N_R = \frac{(3\,m)^2(0.5\ r/s)(995.7\ kg/m^3)}{(0.798 \times 10^{-3}\ N{\bullet}s/m^2)} = 5.6 \times 10^6 \quad \text{(turbulent mixing)}$$

2. Compute the power consumption using Eq. (5-9) in p336.

   $P = N_P \rho n^3 D^5$

   Required data: $N_P = 3.5$ (see Table 5-11 in p338).

$P = (3.5)(995.7\ kg/m^3)(0.5\ r/s)^3 (3\ m)^5 = 105{,}855\ kg{\bullet}m^2/s^3$ (W)

PROBLEM 5-4

Problem Statement - See text, page 448

Solution

1. Determine the speed of rotation when the Reynolds number is 100,000 using Eq. (5-11) in p337.

$$N_R = \frac{D^2 n \rho}{\mu}$$

$$n = \frac{N_R \mu}{D^2 \rho}$$

Pertinent data: $D = 500$ mm = 0.5 m

$N_R = 100{,}000$

$\mu = 1.307 \times 10^{-3}\ N{\bullet}s/m^2$ (Table C-1 in Appendix C, p1915)

$\rho = 999.7\ kg/m^3$ (Table C-1 in Appendix C, p1915)

$$n = \frac{(100{,}000)(1.307 \times 10^{-3}\ N{\bullet}s/m^2)}{(0.5\ m)^2(999.7\ kg/m^3)} = 0.52\ r/s = 31.4\ r/min$$

2. The Reynolds number is related to both turbulence and velocity. Higher Reynolds numbers are indicative of greater turbulence and velocity. As a general rule, the greater the turbulence and the higher the velocity, the more

efficient the mixing operation will be. However, high Reynolds numbers lead to high power requirements. Rearranging Eq. (5-9) and substituting n to include the Reynolds number yields:

$P = N_P \rho n^3 D^5$

$$n = \frac{N_R \mu}{D^2 \rho}$$

$$P = \frac{N_P \mu^3 (N_R)^3}{\rho^2 D}$$

As shown, the power varies directly with the cube of the Reynolds number.

3. Determine the required motor size using the rearranged form of Eq. (5-9) derived above and the pertinent data from the problem statement and step 1.

   a. Compute theoretical power, first converting newtons to kg•m/s^2.

$$(1.307 \times 10^{-3}\ \text{N•s/m}^2)\left[\frac{(1\,\text{kg•m/s}^2)}{\text{N}}\right] = 1.307 \times 10^{-3}\ \text{kg/m•s}$$

$$P = \frac{[(1.7)(1.307 \times 10^{-3}\ \text{kg/m•s})^3 (100{,}000)^3]}{[(999.7\ \text{kg/m}^3)^2 (0.5\ \text{m})]}$$

$= 4.44\ \text{kg•m}^2/\text{s}^3\ (\text{W})$

b. Compute electric motor power requirements

   $P_{motor} = P/e = 4.44\ \text{W}/0.2 = 22.2\ \text{W}$

PROBLEM 5-5

Problem Statement - See text, page 448

Solution

1. Solve the problem for a plug flow reactor. Let N = number of particles

   a. Write the mass balance equation for a plug flow reactor (PFR).

$$dV\frac{dN}{dt} = QN_o - Q(N_o + \frac{dN}{dt}dx) + (-kN)dV$$

assume steady state $\left(\dfrac{dN}{dt} = 0\right)$

$0 = – QdN – kN\ dV$

b. Solve the mass balance equation for N

$$\frac{dN}{N} = \frac{k}{Q} dV$$

$$\ln\frac{N}{N_o} = -k\frac{V}{Q}$$

$N = N_0\ e^{-kV/Q}$

let t = V/Q

$N = N_0\ e^{-kt}$

c. Compute k at t = 10

$$\ln\frac{N}{N_o} = -k\frac{V}{Q}$$

$$\ln\frac{N}{N_o} = -kt$$

Data: N = 3

$N_o = 10$

t = 10 min

$$\ln\frac{3}{10} = -k(10)$$

$k = 0.12\ min^{-1}$

d. Compute N at t = V/Q = 5 min

$N = N_0\ e^{-kt}$

$N = 10\ e^{\ 0.12(5)}$

N = 5.49 particles/unit volume

2. Solve the problem for a batch reactor.

a. Write the mass balance equation for a batch reactor

$$V\frac{dN}{dt} = -kNV$$

$$\frac{dN}{dt} = -kN$$

b. Solve the mass balance equation for N.

$$\frac{dN}{N} = -kdt$$

$$\ln\frac{N}{N_o} = -kt$$

$$N = N_o\,e^{-kt}$$

c. Compute N at t = 5 min.

$N = 10\,e^{-0.12(5)}$

N = 5.49 particles/unit volume

PROBLEM 5-6

Problem Statement - See text, page 448

Solution

1. Write the mass balance for a complete mix reactor.

$$V\frac{dN}{dt} = QN_o - QN + (-kN)V$$

$$\frac{dN}{dt} = \frac{Q}{V}(N_o) - \frac{Q}{V}(N) + (-kN)$$

$$\frac{dN}{dt} + N\left(\frac{Q}{V} + k\right) = N_o\frac{Q}{V}$$

2. Solve the mass balance equation for N

$$\frac{dN}{dt} + N\left(\frac{Q}{V} + k\right) = N_o\frac{Q}{V}$$

This is a first-order linear differential equation and can be solved easily using the integrating factor, $e^{(Q/V + k)t}$.

The final result is:

$$N = \frac{Q}{V}\frac{N_o}{(k + Q/V)}\left[1 - e^{-(k+Q/V)t}\right] + N_o e^{-(k+Q/V)t}$$

3. Determine k at the steady state condition.

   Pertinent data:

   $t = \infty$

   $Q/V = 1/Q = 0.1\ min^{-1}$

   $N_o = 10$

   $N = 3$

   $$N = 0.1\frac{10}{(k + 0.1)}(1 - 0) + 10(0)$$

   $$N = \frac{1}{(k + 0.1)}$$

   $k = 0.233\ min^{-1}$

4. Determine N at t = 5 min

   $$N = 0.1\frac{10}{(0.233 + 0.1)}\left[1 - e^{-(0.233+0.1)5}\right] + 10e^{-(0.233+0.1)5}$$

   N = 2.43 + 1.89 = 4.32 particles/unit volume

PROBLEM 5-7

Problem Statement - See text, page 449.

Instructors Note: Assume air is released 0.25 m above the tank bottom.

Solution

1. Find the power requirement, using Eq. (5-3), page 330.

   $$G = \sqrt{\frac{P}{\mu V}}$$

   $$P = \mu V G^2$$

   Pertinent data: μ at 60°C = 0.466 x 10^{-3} N•s/m^2 (Table C-1)

   $G = 60\ s^{-1}$

$V = 200\ m^3$

$P = (0.466 \times 10^{-3}\ N\bullet s/m^2)(200\ m^3)(60\ s^{-1})^2$

$= 335.5\ N\bullet m/s = 0.336\ kN\bullet m/s\ (kW)$

2. Find the required air flowrate using Eq. (5-14), page 343.

$$P = p_a V_a \ln \frac{p_c}{p_a}$$

$$V_a = \frac{P}{p_a \ln \frac{p_c}{p_a}}$$

Pertinent data:

γ at 60°C =9.642 kN/m^3 (Table C-1)

p_a = atmospheric pressure = (10.33 m H_2O)(9.642 kN/m^3)

= 99.60 kN/m^2

p_c = (p_a + depth of water above release point)•μ

= (10.33 + 3.5) m H_2O × γ = (13.83 m H_2O)(9.642 kN/m^3)

=133.35 kN/m^2

$$V_a = \frac{(0.336\ kN\bullet m/s)}{(99.60\ kN/m^2)\left[\ln\left(\frac{133.35}{99.60}\right)\right]} = 0.011.5\ m^3/s = 0.69\ m^3/min$$

PROBLEM 5-8

Problem Statement - See text, page 449

Solution

1. Find the required air flowrate using Eq. (5-14), p. 343.

$$P = p_a V_a \ln \frac{p_c}{p_a}$$

$$V_a = \frac{P}{p_a \ln \frac{p_c}{p_a}}$$

Pertinent data: $P = 8543\ W = 8.543\ kN•m/s$

γ at 15°C = 9.798 kN/m^3 (Table C-1 in Appendix C)

p_a = atmospheric pressure (10.33 m H_2O x 9.798 kN/m^3)

= 101.21 kN/m^2

p_c = (p_a + depth of water above release point) γ

= (10.33 + 3) m H_2O = 13.33 m H_2O x 9.798 kN/m^3

= 130.61 kN/m^2

$$V_a = \frac{(8.543\ kN \bullet m/s)}{(101.21\ kN/m^2)\left[\ln\left(\frac{130.61}{101.21}\right)\right]} = 0.331\ m^3/s = 19.86\ m^3/min$$

PROBLEM 5-9

Problem Statement - See text, page 449

Solution

1. Derive Stokes' Law by equating Eqs. (5-16) and (5-23).

   Note: Laminar flow conditions apply

   The gravitational force on a particle is expressed by Eq. (5-16) in p. 346:

   $$F_G = (\rho_p - \rho_w)\, gV_p$$

   The frictional drag force on a particle as expressed by Eq. (5-23) in p. 346 for laminar flow conditions is:

   $$F_D = 3\pi\mu\upsilon_p d_p$$

   The drag force is equal to the gravitational force when

   $$(\rho_s - \rho)gV_p = 3\pi\mu\upsilon_p d_p$$

   But $V_p = (1/6)\pi d_p^3$

   $$[(\rho_s - \rho)gV_p][(1/6)\pi d_p^3 = 3\pi\mu\upsilon_p d_p$$

   $$\upsilon_p = \frac{(\rho_s - \rho)\, d_p^2}{18\ \mu}$$

PROBLEM 5-10

Problem Statement - See text, pages 449

Solution

1. Determine the drag coefficient using Eq. (5-19).

$$C_d = \frac{24}{275} + \frac{3}{\sqrt{275}} + 0.34 = 0.608$$

2. Determine the particle settling velocity using Eq. (5-18) and assuming the particle is spherical.

$$\upsilon_{r(t)} = \sqrt{\frac{4g(sg_p - 1)d_p}{3C_d\phi}}$$

$$\upsilon_{r(t)} = \sqrt{\frac{4(9.81\,m/s^2)(2.65 - 1)(1\,mm)(1\,m/10^3\,mm)}{(3)(0.604)(1.0)}} = 0.19\,m/s$$

PROBLEM 5-11

Problem Statement - See text, page 449

Solution

1. Establish a spreadsheet for determining the final settling velocity. Compute N_R using Eq. (5-21) as determined in Step 2 of Example 5-4. Use a sphericity factor of 1.0 for a spherical particle.

$$N_R = \frac{\upsilon_p d_p \psi}{\nu} = \frac{(0.224\,m/s)(0.5\times10^{-3}\,m)(1.0)}{(1.003\times10^{-6}\,m^2/s)}$$
$$= 111.7$$

2. Use Eq. (5-19) as shown in Step 3 of Example 5-4 and assume a settling velocity for each iteration to reach closure.

3. Calculate the drag coefficient, C_d

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 = \frac{24}{111.7} + \frac{3}{\sqrt{111.7}} + 0.34$$
$$= 0.839$$

4. Calculate the particle settling velocity

$$\upsilon_p = \sqrt{\frac{4g(sg-1)d}{3C_d}} = \sqrt{\frac{4(9.81 m/s^2)(2.65-1)(0.5 x 10^{-3})}{3 x 0.839}}$$
$$= 0.113 \text{ m/s}^2$$

5. Set up a spreadsheet as follows

v_p	N_R	$24/N_R$	$\sqrt{N_R}$	$3/\sqrt{N_R}$	0.34	C_d	$(v_p)^2$	v_p
0.088	43.868	0.55	6.623	0.45	0.34	1.34	0.00805	0.0897
0.090	44.865	0.53	6.698	0.45	0.34	1.32	0.00816	0.0903

Closure has been achieved.

6. The Reynolds number, N_R, is 44.865 and coefficient of drag, C_d , is 1.32.

PROBLEM 5-12

Problem Statement - See text, page 449

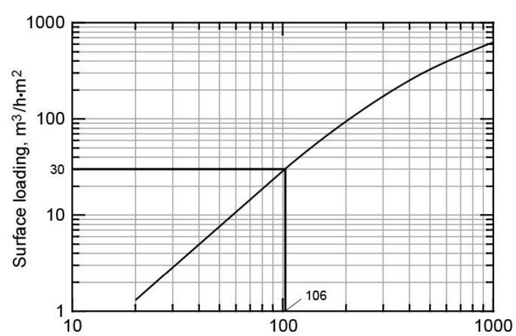
Solution

Following conditions are specified in the problem statement:

Peak flow = 40,000 m^3/d
Design SES = 106 µm

1. Find size of vortex grit removal units.

   a. Find surface loading rate. Use Fig. 5-34(b) to determine surface loading rate for SES = 106 µm.



Select surface loading rate = 30 $m^3/h\bullet m^2$

   b. Find area (A) required

$$A = \frac{\text{Peak flow}}{\text{Surface loading rate}}$$

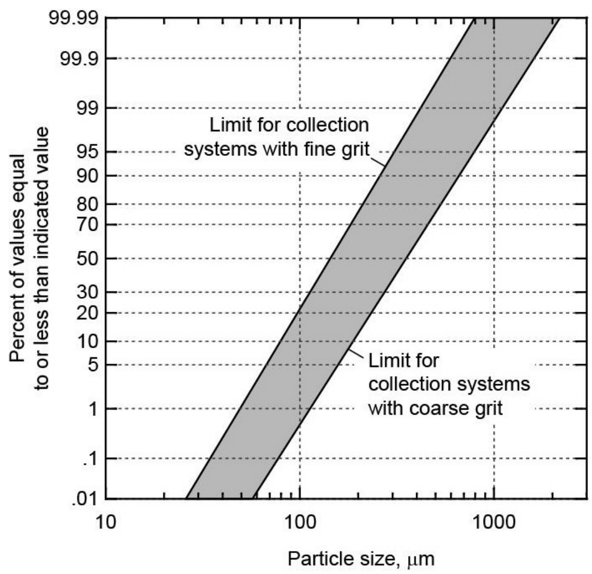
Peak flow = 40,000 m^3/d = 1667 m^3/h

$$A = \frac{(1667\ m^3/h)}{(30\ m^3/h \cdot m^2)} = 55.5\ m^2$$

In actual practice, it is necessary to review manufacturers' catalog information to determine number of units and model size to provide required settling area.

2. Determine the expected grit removal if the facility is located in an area that is known to have fine grit.

Use Fig. 5-31



The range of particle sizes for various US treatment plants is illustrated on Figure 5-31. For 106 μm SBS and fine grit (upper limit of range), about 30% of the particles will be ≤ 106 μm. Therefore, expected grit removal = (100 – 30)% = 70%.

3. To achieve 90% removal, find the Design SBS.

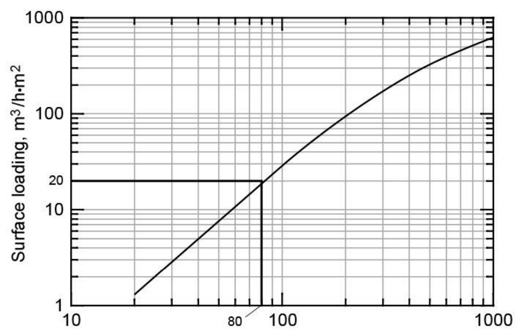
Use Fig. 5-31 (see Step 2)

To achieve 90% removal, 10% of the particles must be ≤ 80 μm.

4. Find surface loading rate for SBS = 80 μm.

Use Fig 5-34(b)

For SBS = 80 μm



Surface loading rate = 20 $m^3/h•m^2$

5. Fine area required for SBS = 80 μm.

$$A = \frac{(1667\,m^3/h)}{(20\,m^3/h \cdot m^2)} = 83.35\,m^2$$

To get 90% removal, the surface area has to be increased from 55.5 m^2 to 83.35 m^3 (50% increase).

PROBLEM 5-13

Problem Statement - See text, page 449

Solution

A variety of solutions are possible. The following data have been assumed (see Table 5-17, page 374).

Detention time at Q_{max} = 3 min

Water depth = 4 m

Diffuser submergence = 3 m

Number of chambers = 2 (each channel can service 75% of the peak flow with one channel out of service)

Air supply rate = 0.3 $m^3/m•min$ of length

Length to width ratio = 4:1

1. Using the data given above, determine the tank dimensions.

V/Q = 3 min at peak flowrate (20,000 m^3/d per channel)

$$V = \frac{(3\,\text{min})(20{,}000\,\text{m}^3/\text{d})}{(60\,\text{min/h})(24\,\text{h/d})} = 41.7\,\text{m}^3$$

$$A_s = \frac{41.7\,\text{m}^3}{4\,\text{m}} = 10.4\,\text{m}^2$$

Length x width = 4w x w = $4w^2$ = 10.4 m^2
Width = 1.6 m
Length = 6.4 m

2. Determine the maximum air requirement.

$$Q_{air} = \left(\frac{0.3\,\text{m}^3}{\text{m}\bullet\text{min}}\right)(6.4\,\text{m})(2\text{ channels}) = 3.84\ \text{m}^3/\text{min}$$

3. Determine the horsepower requirements. Assume the blower efficiency is 70%. The specific weight of water is 9.81 kN/m^3 (9,810 N/m^3) (Appendix C). 1 W = 1 J/s or 1 N•m/s (Table 2 in Front section) Thus, 1 kW = 1000 N•m/s.

h = 0.250 m (diffusers) + 3 m (submergence) + 0.40 m = 3.65 m

h = (3.65 m)(9810 N/m^3) = 35,806 N/m^2

$$\text{Power} = \left(\frac{Q_{air}h}{\text{efficiency}}\right)$$

$$\text{Power} = \left[\frac{(3.84\ \text{m}^3/\text{min})(35{,}806\ \text{N/m}^2)}{(0.70)(60\ \text{s/min})}\right]\left(\frac{1\,\text{kW}}{1000\ \text{Ngm/s}}\right) = 3.274\ \text{kW}$$

4. Determine the power cost. Assume the electric motor efficiency is 92%.

$$\text{Power cost} = \left[\frac{(3.724\ \text{kW})(24\,\text{h/d})}{(0.9)}\right](\$0.12/\text{kWh}) = \$10.48/\text{d}$$

Note: In the above computation, it was assumed that the blower operates at maximum capacity regardless of average flow or peak flow conditions. In small plants, this situation is often the case. Under actual operating conditions in other plants, the blower capacity is adjusted to maintain an optimum air rate, thus the power consumption may be less than that calculated in the above example.

PROBLEM 5-14

Problem Statement - See text, page 449

Solution

The given data are:

Detention time at Q_{max} = 3.5 min

Width to depth ratio = 1.5 : 1

Air supply rate = 0.4 m^3/m•min of tank length

Water depth = 3 m

Average flowrate = 0.3 m^3/s

Peak flowrate = 1 m^3/s

1. Using the data given above, determine the tank dimensions.

   V/Q_{max} = 3.5 min at peak flow

   V = (3.5 min)(1 m^3/s)(60 s/min) = 210 m^3

   Depth = 3 m

   Width = 1.5 x 3 m = 4.5 m

   $$\text{Length} = \frac{210\,\text{m}^3}{3\,\text{m x } 4\,\text{m}} = 15.6\,\text{m}$$

2. Determine the air requirement assuming 0.4 m^3/m•min (see Table 5-17 on page 374).

   $$Q_{air} = \frac{0.4\,\text{m}^3}{\text{m}\bullet\text{min}}(15.6\,\text{m}) = 6.2\,\text{m}^3/\text{min}$$

PROBLEM 5-15

Problem Statement - See text, page 449

Solution

1. The advantages and disadvantages of an aerated grit chamber as compared to a vortex grit chamber are:
   - Air flowrate can be adjusted to optimize grit removal over a wide range of wastewater flowrates
   - Grit contains relatively low amounts of organic matter, therefore, the unit does not require an external grit washer
   - Aeration may freshen wastewater and improve performance of downstream processes, however, aeration may release volatile organic compounds (VOCs) and odors, thus covering of the tanks may be required.
   - Can be used for chemical mixing and flocculation
   - No maximum size limit
   - Some short circuiting may occur thus requiring installation of internal baffling in the tanks to enhance grit removal
2. The advantages and disadvantages of a vortex grit chamber as compared to an aerated grit chamber are:
   - Unit has shorter detention time (30 s), and is compact, therefore, requires less space
   - No submerged diffusers or parts that require maintenance
   - Turbulence in the vortex may release odors and VOCs, but the area requiring covering is smaller than an aerated grit chamber.
   - Lower construction cost
   - Proprietary design; deviations from manufacturer’s recommended design may void performance guarantee
   - Unit does not require an external blower system, but may require an air lift pump to remove grit
   - Air lift pumps are often not effective in removing grit from sump
   - Lower power consumption as compared to an aerated grit chamber

Reference:,

WEF (1998) *Design of Municipal Wastewater Treatment Plants*, 4th ed., vol. 2, Water Environment Federation, Alexandria, VA.

PROBLEM 5-16

Problem Statement - See text, page 449

Solution

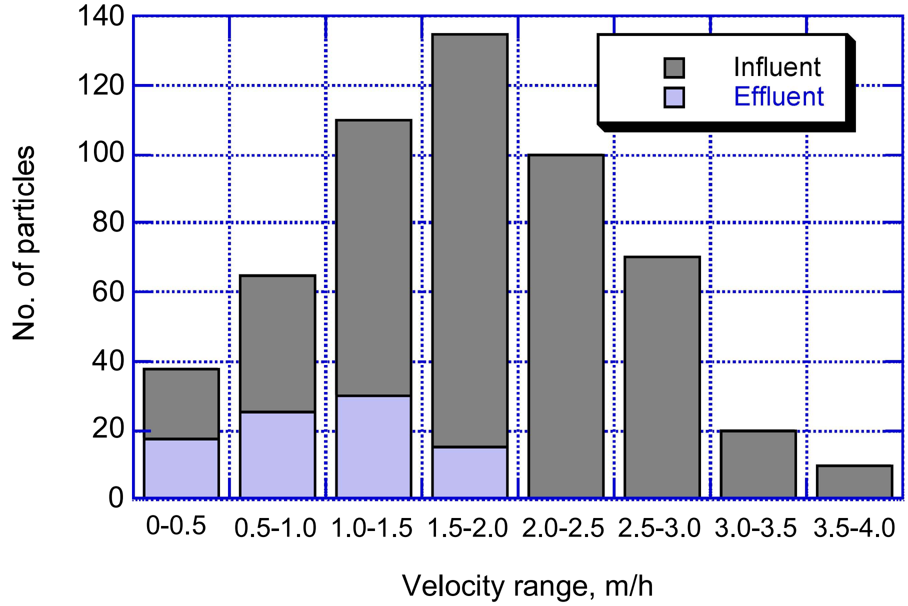
1. Prepare a computation table to determine the particle distribution in the effluent.

No. of particles in influent	V_{avg}, m/h	V_{avg},/ V_c	No. of particles removed, (V_{avg}/V_c x N_o)	No. of particles in effluent (N_o-N)
20	0.25	0.125	2.5	17.5
40	0.75	0.375	15	25
80	1.25	0.625	50	30
120	1.75	0.875	105	15
100	2.25	>1	100	0
70	2.75	>1	70	0
20	3.25	>1	20	0
10	3.75	>1	10	0
Σ = 460			372.5	87.5

2. Determine the removal efficiency.

$$\text{Percent removal} = \left(\frac{372.5}{460}\right)100 = 81.0\%$$

3. Plot the particle histogram for the influent and effluent wastewater.



PROBLEM 5-17

Problem Statement - See text, page 450

Solution

1. Determine the removal efficiency for particles with an average settling velocity of 1 m/hr and a tray depth of 1 m.

   a. The percent removal of the particles above the tray is:

   $V_{critical}$ = 1 m/1h = 1 m/h

$$\%\,\text{removal} = \frac{V_{solids}}{V_{critical}} \times 100 = \frac{(1\text{ m/h})}{(1\text{ m/h})}(100) = 100\%$$

   b. The percent removal of the particles below the tray is:

   $V_{critical}$ = 2 m/1h = 2 m/h

$$\%\text{ removal} = \frac{V_{solids}}{V_{critical}} \times 100 = \frac{(1\text{ m/h})}{(2\text{ m/h})}(100) = 50\,\%$$

   c. Assuming all particles are evenly distributed, the overall removal efficiency is:

$$\%\ \text{removal} = \frac{(100)(1\text{m}) + (50)(2\text{m})}{3\text{m}} = 67\%$$

2. Determine the effect of tray depth, d, on removal efficiency for particles with an average settling velocity of 1 m/h.

   a. For d ≤ 1 m

$$\%\text{removal} = \left[(1)\left(\frac{d}{3}\right) + \left(\frac{1}{3-d}\right)\left(\frac{3-d}{3}\right)\right](100) = [(d/3) + (1/3)](100)$$

   b. For 1 m ≤ d ≤ 2m

$$\%\text{removal} = \left[\left(\frac{1}{d}\right)\left(\frac{d}{3}\right) + \left(\frac{1}{3-d}\right)\left(\frac{3-d}{3}\right)\right](100) = [(1/3) + (1/3)](100)$$

$$= (2/3)\ (100\ \%)$$

   c. For 2 m ≥ d ≥ 3 m

$$\%\ \text{removal} = \left[\left(\frac{1}{d}\right)\left(\frac{d}{3}\right) + (1)\left(\frac{3-d}{3}\right)\right](100) = [(1/3) + 1 - (d/3)](100)$$

$$= [(4-d)/3](100)$$

   The maximum removal efficiency is achieved by placing the tray anywhere between 1 m and 2 m. For particles with settling velocities of 1 m/h, 66.7 percent removal efficiency is achieved. Therefore, by moving the tray from 1.0 m, the efficiency cannot be improved.

3. Determine the overall efficiency as a function of the depth of the tray for particles with a settling velocity of 0.3 m/h.

   a. For d ≥ 0.3 m

$$\%\ \text{removal} = \left[\left(\frac{1}{d}\right)\left(\frac{d}{3}\right) + \left(\frac{0.3}{3-d}\right)\left(\frac{3-d}{3}\right)\right](100)$$

$$= [(d/3) + (0.3/3)](100) = [(d/3) + 0.1](100)$$

   b. For 0.3 m ≥ d ≥ 2.7 m

$$\% \text{removal} = \left[\left(\frac{0.3}{d}\right)\left(\frac{d}{3}\right) + \left(\frac{0.3}{3-d}\right)\left(\frac{3-d}{3}\right)\right](100)$$

= [(0.3/3) + (0.3/3)](100) = 20%

c. For 2.7 m ≥ d ≥ 3.0 m

$$\% \text{removal} = \left[\left(\frac{0.3}{d}\right)\left(\frac{d}{3}\right) + (1)\left(\frac{3-d}{3}\right)\right](100)$$

= [0.1 + 1 – (d/3)] (100) = [1.1 – (d/3)](100)

PROBLEM 5-18

Problem Statement - See text, page 450

Solution

1. Try a settling velocity of 0.085 m/s and calculate the Reynolds number. Use the Reynolds number to determine the drag coefficient, and use the drag coefficient in Newton's equation to find the settling velocity.

$$N_R = \frac{0.85\,(0.085\,\text{m/s})(0.5 \times 10^{-3}\,\text{m})}{(1.003 \times 10^{-6}\,\text{m}^2/\text{s})} = 36.0$$

$$C_d = \frac{24}{36.0} + \frac{3}{\sqrt{36.0}} + 0.34 = 1.507$$

$$\upsilon_p = \sqrt{\frac{4\,(9.81\,\text{m/s}^2)(2.65-1)(0.5 \times 10^{-3}\,\text{m})}{3 \times 1.507}} = 0.085\,\text{m/s}$$

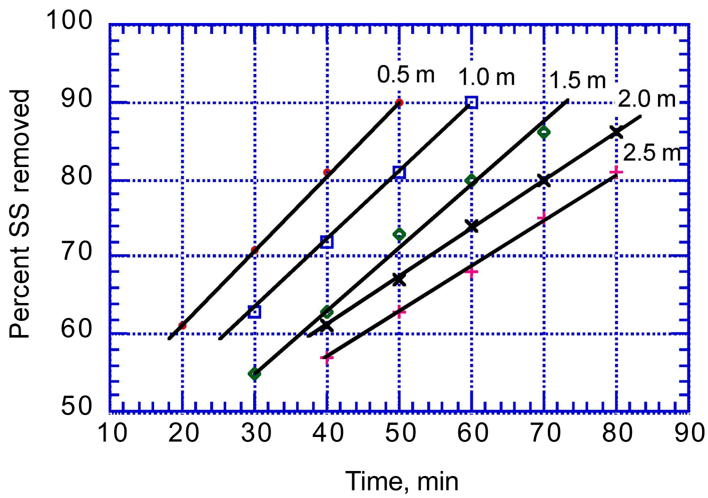
Closure has been achieved.

PROBLEM 5-19

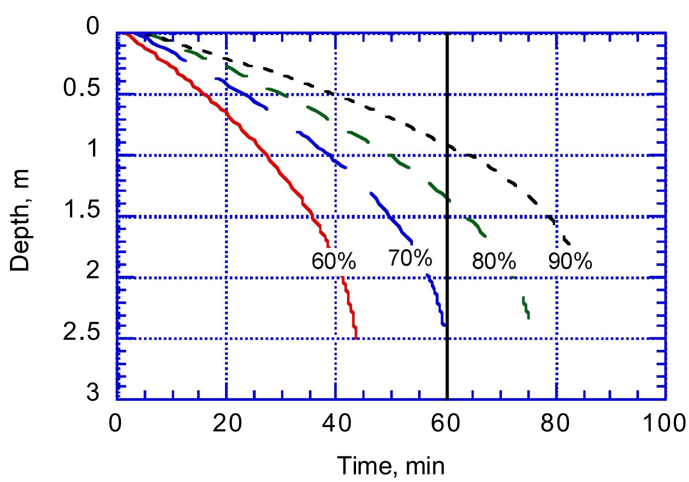
Problem Statement - See text, page 450

Solution

1. Plot the percent suspended solids removed versus time for each increment of depthas shown below.



2. From the above plot, pick off the data points at intervals of percent removal to create a particle settling curve similar to Fig. 5-234 as shown below.



3. Calculate the detention time for the basin using Eq. (5-26).

Detention time = depth/v_c

Detention time = 3 m/(3 m/h) = 1 h (60 min)

5 Determine the efficiency of removal using Eq. (5-32) and data points from the plot in step 2 at t = 60 min. Set up a table as shown below.

$\frac{\Delta h_n}{h_t} \times \frac{R_n + R_{n+1}}{2} =$ percent removal	
$\frac{0.9}{3} \times \frac{100+90}{2} =$	28.5
$\frac{0.4}{3} \times \frac{90+80}{2} =$	11.3
$\frac{1.2}{3} \times \frac{80+70}{2} =$	30.0
Total	69.8

PROBLEM 5-20

Problem Statement - See text, page 450

Solution

1. Assuming water velocity u = 1 m/s, calculate the settling velocity for countercurrent and cocurrent conditions. As stated in the problem statement, the inclined plates length is 2.0 m, plate specing is 75 mm.

   a. Calculate us for countercurrent using Eq. (5-35):

   $$\upsilon_s = \frac{u \circ d}{L\cos\theta + d\sin\theta}$$

   For θ = 40°

   $$\upsilon_s = \frac{(1.0\ \text{m/s})(75\ \text{mm})(1\ \text{m}/10^3\ \text{mm})}{(2\ \text{m})\cos(40°) + (75\ \text{mm})(1\ \text{m}/10^3\ \text{mm})\sin(40°)}$$

   $$\upsilon_s = 0.047\ \text{m/s}$$

   b. Calculate υ_s for cocurrent using Eq. (5-38):

   $$\upsilon_s = \frac{u \circ d}{L\cos\theta - d\sin\theta}$$

   For θ = 40°

   $$\upsilon_s = \frac{(1.0\ \text{m/s})(75\ \text{mm})(1\ \text{m}/10^3\ \text{mm})}{(2\ \text{m})\cos(40°) - (75\ \text{mm})(1\ \text{m}/10^3\ \text{mm})\sin(40°)}$$

$\upsilon_s = 0.051\,\text{m/s}$

2. Similarly, calculate the settling velocity for 50 and 60 degrees. The results are summarized in the table below. As shown, the cocurrent arrangement results in greater settling velocities.

			Countercurrent flow Inclination angle, °			Cocurrent flow Inclination angle, °		
	Symbol	Unit	40	50	60	40	50	60
Assumed water velocity:	u	m/s	1.00	1.00	1.00	1.00	1.00	1.00
Settling velocity	υ_s	m/s	0.047	0.056	0.070	0.051	0.061	0.080

PROBLEM 5-21

Problem Statement - See text, page 450

Solution

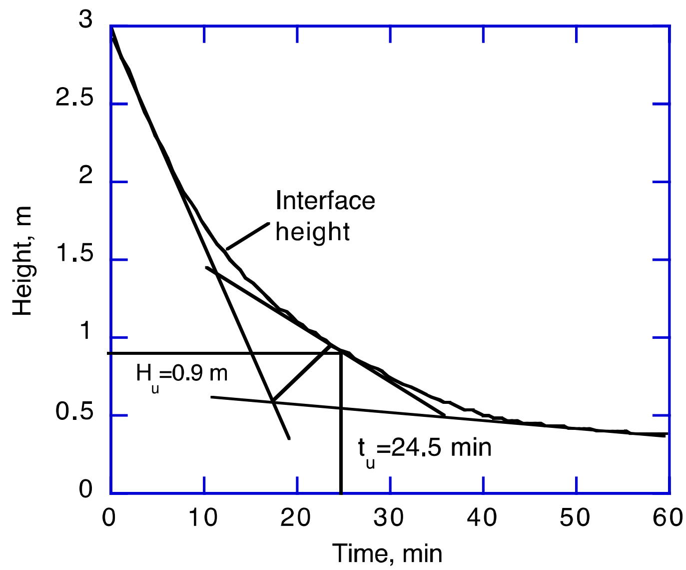
1. Determine the area required for thickening using Eq. (5-41).

   a. Determine the value of H_u

$$H_u = \frac{C_o H_o}{C_u}$$

$$H_u = \frac{(3600\,\text{g/m}^3)(3.0\,\text{m})}{(12{,}000\,\text{g/m}^3)} = 0.9\,\text{m}$$

   b. Determine t_u from the plot using the procedure described in Example 5-7.



c. Determine the thickening area.

$$A = \frac{Qt_u}{H_o} = \left[\frac{(1500\,m^3/d)(24.5\,min)}{(24\,h/d)(60\,min/h)(3\,m)}\right]$$
$$= 8.5\,m^2$$

PROBLEM 5-22

Problem Statement - See text, pages 450

Solution

1. Assumptions and design criteria:

   a. Assume primary tank is followed by secondary treatment and waste activated sludge is not returned to primary settlng tank

   b. Overflow rate at average flow = 40 $m^3/m^2 \cdot d$

2. Determine the required surface area and volume.

$$A_s = \frac{(45{,}000\text{ persons})(400\text{ L/capita}\cdot\text{d})(1\text{ m}^3/10^3\text{ L})}{(40\,\text{m}^3/\text{m}^2\cdot\text{d})} = 450\text{ m}^2$$

$$V = \frac{(45{,}000\text{ persons})(400\text{ L/capita}\cdot\text{d})(1\text{ m}^3/10^3\text{ L})(2\text{ h})}{(24\text{ h/d})} = 1500\text{ m}^3$$

3. Determine diameter and depth

$$\text{Diameter} = \sqrt{\frac{450\,\text{m}^2}{(\pi/4)}} = 23.94\text{ m}$$

Use a diameter of 24 m

$$\text{Depth} = \frac{1500\,\text{m}^3}{(\pi/4)(24\,\text{m})^2} = 3.3\text{ m}$$

Use a depth of 3.5 m

Comment: The depth is within the range of depths (3-4.9 m) given in Table 5-20. Consideration should be given to increasing the depth to 4-4.5 m if the tank is used for thickening primary sludge.

PROBLEM 5-23

Problem Statement - See text, page 450-451

Solution

1. Determine the horizontal settling velocity in the tank.

$$V_{horiz} = \frac{Q}{A_{horiz}} = \frac{(\text{Overflow rate})(A_s)}{A_{horiz}} = \frac{(30\text{ m}^3/\text{m}^2\bullet\text{d})(6\,\text{m}\times 15\,\text{m})}{(2.75\,\text{m}\times 6\,\text{m})(24\text{ h/d})(3600\text{ s/h})}$$
$$= 0.0019\text{ m/s}$$

2. Determine the scour velocity V_H using Eq. (5-46) on page 396.

$$V_H = \left[\frac{8k(s-1)gd}{f}\right]^{1/2}$$

$$V_H = \left[\frac{(8)(0.04)(2.5-1)(9.81\text{m/s}^2)(0.1\text{mm})}{(0.03)(10^3\text{ mm/1m})}\right]^{1/2} = 0.125\text{ m/s}$$

Because the horizontal velocity in the tank is less than the scour velocity, the particles will not be scoured.

PROBLEM 5-24

Problem Statement - See text, page 451

Solution

1. Determine the percentage increase in hydraulic loading.

$$\text{Increase, \%} = \left[\frac{(200\,\text{m}^3/\text{d})}{(20{,}000\,\text{m}^3/\text{d})}\right](100) = 1\%$$

2. Determine the percentage increase in organic loading.

$$\text{Increase, \%} = \left[\frac{(200\,\text{m}^3/\text{d})(2000\,\text{g/m}^3)}{(20{,}000\,\text{m}^3/\text{d})(350\,\text{g/m}^3)}\right](100) = 5.7\%$$

3. Discuss the effect of the incremental loadings on the performance of the settling facilities.

   The design overflow rate of 32 $m^3/m^2 \bullet d$ specified in the problem is at the upper end of the design overflow rate specified in Table 5-19 for primary settling with waste sludge return at the average flowrate. The increase in hydraulic loading of 1 percent resulting from the return sludge flow is small and in itself is not significant. The overflow rate at peak hourly flow should be checked to ensure adequate settling occurs.

   An additional piece of data given in the problem is the 2.8 h detention time in the clarifier, for the average flowrate. The detention time is longer than the typical value of 2.0 h given in Table 5-19. The value of the detention time in this problem is that additional clarifier depth is provided. The increased depth will provide an increased safety factor in short circuiting and sludge blanket carryover. Based on the information in the example, the probable effect on primary clarifier performance of adding the return waste activated sludge is negligible during average flow periods. During peak hourly flows, some increase in solids carryover from the primary clarifier might be expected.

   In actuality, if the waste activated sludge has poor settling characteristics, performance of the primary clarifier may suffer at average flows as well as during the peak flow periods. The addition of a baffle as shown on Fig. 8-56 may retard the carryover of waste activated sludge solids. A disadvantage of not providing separate thickening for waste activated sludge is the lack of control for managing the sludge during upset or poor performance conditions.

PROBLEM 5-25

Problem Statement - See text, page 451

Instructional Guidelines

The purpose of this problem is two-fold: (1) to familiarize students with some of the additional sources of information that are available and (2) to provide insight into the range of values that will be found in the literature for a given design parameter. It will be helpful to the students if some of the standard reference publications, especially those from the Water Environment Federation, are made available or placed on reserve in the library.

PROBLEM 5-26

Problem Statement - See text, page 451

Solution

1. The advantages of circular primary sedimentation tanks are:
   - More economical to construct than rectangular tanks where site constraints are not a problem
   - Simplest mechanical equipment for sludge and scum removal
   - Collector equipment requires less maintenance than chain-and-flight mechanisms
   - Center flocculation compartment can be incorporated if combined flocculation-clarification feature is required
   - Less sensitive to rag accumulations on collector mechanisms
   - Less sensitive to flowrate surges provided tank inlet is properly baffled
2. The advantages of rectangular primary sedimentation tanks are:
   - Less space (area) required when multiple units are used
   - On large installations, common-wall construction can be used that saves construction costs

- Common pipe galleries can be used that facilitate pipe installation and equipment maintenance
- Longer travel distance for settling to occur
- Performance less affected by high winds
- Covering easier if required for odor control or VOC containment

References

Examples of references used are listed below.

AWWA/ASCE (2012): *Water Treatment Plant Design*, 5th ed., American Water Works Association/American Society of Civil Engineers McGraw-Hill, New York.

Parker, D.S., M. Sequer, M. Hetherington, A.Z. Malik, D. Robison, E.J. Wahlberg, J. Wang (2000) "Assessment and Optimization of a Chemically Enhanced Primary Treatment System," Proceedings of the WEF 73rd ACE, Anaheim, CA.

WEF (2005) *Clarifier Design, Manual of Practice FD-8*, 2nd ed., Water Environment Federation, Alexandria, VA.

WEF (2009) *Design of Municipal Wastewater Treatment Plants*, 5th ed., WEF Manual of Practice No. 8, ASCE Manual and Report on Engineering Practice No. 76, Water Environment Federation, Alexandria, VA.

WEF/IWA (2003) *Wastewater Treatment Plant Design, Student Workbook*, Water Environment Federation, Alexandria, VA.

PROBLEM 5-27

Problem Statement - See text, page 451

Instructors Note: There are many possible solutions to this problem; a range of typical values is presented below. The student should be advised that other reference sources would have to be consulted, as some of the required information cannot be found in this text.

Problem Analysis

		Operation	
Parameter	Unit	Sedimentation	Dissolved air flotation

Detention time		1-3 h	10-40 min
Surface loading,	$m^3/m^2 \bullet d$	25-30	60-240
Removal efficiency			
BOD	%	25-40	20-35
TSS	%	40-60	40-60
Power input,	$kWh/10^3\ m^3 \bullet d$	0.35-0.70	2.1-3.5
Application		Removal of settleable solids	Removal of finely divided suspended solids, oil and grease, and scum

PROBLEM 5-28

Problem Statement - See text, page 451

Instructors Note: The detailed solution is provided for mixed liquor. Values calculated for settled activated sludge and primary sludge with activated sludge are summarized in the table.

Solution

1. Using Eq. (5-47) compute required pressure. Assume a typical fraction of air dissolved, f = 0.5. Air solubility at temperature = 20 °C is 18.7 mg/L (see page 407).

$$\frac{A}{S} = \frac{(1.3)[S_a(f \cdot P - 1)]}{S_a}$$

$$0.02 = \frac{(1.3 \text{ x} 18.7 \text{ mL/L})[0.5(P - 1)]}{(2500 \text{ mg/L})}$$

P = 6.1 atm

Gauge Pressure: $P = 6.1 \text{ atm} = \dfrac{\rho + 101.35}{101.35}$

ρ = 518 kPa

2. Determine the required surface area.

$$A = \frac{(1200\,m^3/d)(10^3\,L/1\,m^3)}{(10\,L/m^2\cdot min)(1440\,min/d)} = 83.3\,m^2$$

3. Check the solids loading rate:

Typical range is 1.2 to 3.0 → OK

		Data Set		
		1	2	3
Item	Unit	Mixed liquor	Settled activated sludge	Primary + activated sludge
Solids concentration	mg/L, % solids	2500	0.75	1.00
Optimum A/S Ratio	ratio	0.02	0.03	0.03
Temperature	°C	20	20	20
Surface loading rate	$L/m^2\cdot min$	10	15	8
Flow rate	m^3/d	1200	400	800
Fraction of saturation assumed		0.5	0.5	0.5
Solution (See Example 5-11)				
Required pressure, P	atm	6.11	20.51	26.68
Gage pressure, p	kPa	518	1977	2603
Gage pressure, p	$lb/in.^2$	75.2	286.8	377.5
Required surface area, A	m^2	83.3	18.5	69.4
Solids loading rate, SLR	$kg/m^2\cdot d$	36	162	115
Solids loading rate, SLR	$kg/m^2\cdot h$	1.5	6.75	4.8
Typical SLR (Table 14-20)	$kg/m^2\cdot h$	1.2 - 3.0	2.4 - 4.0	3.0 - 6.0
Check the loading rate		OK!	Too high, consider chemical addition	OK!

PROBLEM 5-29

Problem Statement - See text, page 451

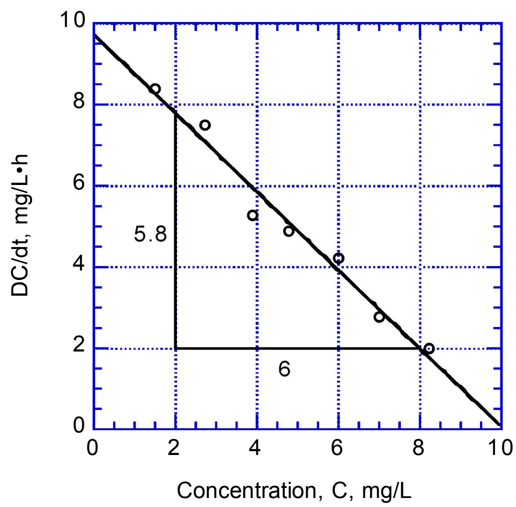
Solution

1. Determine K_La and C_S at 24°C. To determine K_La by graphical analysis, rearrange Eq. (5-61) in a linear form. Eq. (5-61) is equivalent to Eq. (5-71), except the oxygen uptake term r_M is zero.

$$r_C = \frac{dC}{dt} = K_La\,(C_s - C)$$

$$\frac{dC}{dt} = -K_La(C) + K_La(C_s)$$

2. Plot dC/dt versus C



The slope is equal to $-K_La$, so

$-K_La = \dfrac{-5.8}{6}$, $K_La = 0.97\ h^{-1}$

The y-intercept is equal to K_La (C_S), Thus C_s

$$C_s = \frac{9.7}{0.97} = 10.0\ mg/L \text{ at } 24°C$$

C_s is the equilibrium dissolved-oxygen concentration in the test tank.

2. Determine K_La at 20°C. Use Eq. (5-74)

$$(K_La)_T = (K_La)_{20°C}\,\theta^{T-20°C}$$

$K_La_{20°C} = 0.91\ h^{-1}$

PROBLEM 5-30

Problem Statement - See text, page 452

Solution

1. The oxygen transfer efficiency is the amount of oxygen transferred divided by the amount of oxygen delivered to the system. At T = 20°C and C = 0, the oxygen transfer rate is at its maximum.

$$r_c = \frac{dC}{dt} = K_L a(C_s - C) = K_L a(C_s)$$

The saturation concentration of oxygen in water at 20°C and 1 atmosphere can be found in Appendix D.

C_s = 9.08 mg/L

The maximum rate of oxygen transfer, then, is

$$r_c = \frac{dC}{dt} = K_L a(C_s) = (0.91/\text{h})(9.08\ \text{mg/L}\bullet\text{h})$$

2. The mass of oxygen delivered can be calculated by using the ideal gas law.

$$\text{Mass}\,O_2\ \text{transfered} = \left(\frac{2\ \text{m}^3}{\text{min}}\right)(0.21)\left(\frac{1\ \text{mole}}{22.4\,\text{L}}\right)\left(\frac{32\ \text{g}}{\text{mole}}\right)\left(\frac{10^3\ \text{L}}{\text{m}^3}\right) = 600\ \text{g/min}$$

3. For a volume of 100 m^3 and a flowrate of 2 m^3/min, the maximum oxygen-transfer efficiency can be determined using the following expression derived in Example 5-15:

$$E = \frac{(dm/dt)_{20°C, C=0}}{M}$$

where E = oxygen transfer efficiency

$(dm/dt)_{20°C,\ C\,=\,0}$ = oxygen-solution rate at 20°C and zero dissolved oxygen

M = mass rate at which oxygen is introduced

Translating the above equation into practical terms yields

$$E = \frac{V(K_L a)(C_s - C)}{(Q_{air})(\rho_{air})(0.23)}$$

The pertinent data are:

V = 100 m^3

K_La = 0.91/h at 20°C

C_s = 9.08 mg/L

Q_{air} = 2 m^3/min

ρ_{air} = 1.2047 g/L at 20 °C and 760 mm Hg

$$E, \% = \frac{(100\ m^3)(0.91/h)(9.08 mg/L)(100)}{(2m^3/min)(1.2047 g/L)(0.23)(10^3 mg/g)(60\ min/h)} = 2.49\%$$

PROBLEM 5-31

Problem Statement - See text, page 452

Solution

1. Use the equation developed in Example 5-15.

$$Q_a = 3.53 \times 10^{-3} \frac{Q(C_s)_{20°C}}{E(1.024)^{(T-20)}}\left[\ln\left(\frac{C_s - C}{C_s - C_o}\right)\right]$$

where:

Q_a = required air flowrate, m^3/s

Q = wastewater flowrate, m^3/s

C_s = saturation concentration of oxygen at 20°C, g/m^3

C = initial dissolved oxygen concentration, g/m^3

C_o = dissolved oxygen concentration at outlet, g/m^3

E = oxygen transfer efficiency

T = water temperature, °C

2. Determine the required flowrate at 15°C.

From Appendix D, the saturation concentration of oxygen in water at 1 atm is 9.08 mg/L at 20°C, 10.07 mg/L at 15°C, and 8.24 mg/L at 25°C.

Other pertinent data are:

Q = 20,000 m^3/d = 13.89 m^3/min

E = 0.06

$$Q_a = 3.53 \times 10^{-3} \frac{(13.89\ m^3/min)(9.08\ g/m^3)}{0.06(1.024)^{(15-20)}}\left[\ln\left(\frac{10.07 - 0}{10.07 - 4.0}\right)\right] = 4.22\ m^3/min$$

3. The required flowrate at 25°C is:

$$Q_a = 3.53 \times 10^{-3} \frac{(13.89\ m^3/min)(9.08\ g/m^3)}{0.06(1.024)^{(25-20)}}\left[\ln\left(\frac{8.24-0}{8.24-4.0}\right)\right] = 4.35\ m^3/min$$

PROBLEM 5-32

Problem Statement - See text, page 452

Solution

1. Determine the actual oxygen transfer rate under field conditions using Eq. (5-70)

$$AOTR = SOTR\left(\frac{\beta C_{\bar{s},T,H} - C_L}{C_{s,20}}\right)(1.024^{T-20})(\alpha)(F)$$

Neglecting the biological oxygen uptake, the average dissolved oxygen saturation concentration in clean water in aeration tank at temperature T and altitude H can be estimated using the following expression.

$$C_{\bar{s},T,H} = (C_{s,T,H})\left(\frac{P_d + P_{w,mid\ depth}}{P_{atm,H}}\right)$$

From Appendix D, the saturation concentration of oxygen in water at 1 atm is 9.08 mg/L at 20°C. One atmosphere of pressure is equal to 10.333 m of water (see inside of back cover). Thus, the saturation concentration at the tank mid depth is:

$$C_{\bar{s},T,H} = (9.08\ mg/L)\left[\frac{10.333\ m + 0.5(4.5m)}{10.333\ m}\right] = 11.06\ mg/L$$

2. Determine the standard oxygen transfer rate for the ceramic domes (α = 0.64):

Assume β = 0.95, C_L = 2.0 mg/L, and F = 1.0.

$$7000\ kg/d = SOTR\left(\frac{0.95\ (11.06) - 2.0}{9.08}\right)(1.024^{20-20})(0.64)(1)$$

$$SOTR = 11{,}674\ kg/d$$

3. Determine the standard oxygen transfer rate for the non porous diffusers (α = 0.75):

   Assume β = 0.95, C_L = 2.0 mg/L, and F = 1.0.

   $$7000\ \text{kg/d} = \text{SOTR}\left(\frac{0.95\,(11.06) - 2.0}{9.08}\right)(1.024^{20-20})(0.75)(1)$$

   $$\text{SOTR} = 9{,}962\ \text{kg/d}$$

4. Estimate the air required.

   From Table 5-28, use the following oxygen transfer efficiency values

   Ceramic domes (grid pattern) = 27%

   Nonporous diffusers (dual spiral roll) = 12%

   From Appendix B, the density of air at 20°C and 1.0 atmosphere equals 1.204 g/L. Also air contains 23 percent oxygen by mass.

   a. Air requirement for ceramic domes

   $$\text{Air required} = \frac{(11{,}674\ \text{kg/d})}{(1.204\ \text{kg/m}^3)(0.23)(0.27)} = 156{,}135\ \text{m}^3/\text{d}$$

   b. Air requirement for nonporous diffusers

   $$\text{Air required} = \frac{(9{,}962\ \text{kg/d})}{(1.204\ \text{kg/m}^3)(0.23)(0.12)} = 299{,}786\ \text{m}^3/\text{d}$$

PROBLEM 5-33

Problem Statement - See text, page 452

Solution

1. Determine oxygen saturation concentration at mid-depth for winter conditions.

   From Appendix D, the saturation concentration of oxygen in water at 1 atm is 11.28 mg/L at 20°C. One atmosphere of pressure is equal to 10.333 m of water (see inside of back cover). Thus the saturation concentration at the tank mid-depth is:

   $$C_{\overline{s},T,H} = (11.28\ \text{mg/L})\left[\frac{10.333\ \text{m} + 0.5\,(4.5\text{m})}{10.333\ \text{m}}\right] = 13.74\ \text{mg/L}$$

2. Determine the standard oxygen transfer rate for the ceramic domes (α = 0.64):

   Assume β = 0.95, C_L = 2.0 mg/L, and F = 1.0.

$$7000 \text{ kg/d} = \text{SOTR}\left(\frac{0.95\,(13.74) - 2.0}{9.08}\right)(1.024^{20-20})(0.64)(1)$$

$$\text{SOTR} = 8{,}985 \text{ kg/d}$$

3. Determine the standard oxygen transfer rate for the non porous diffusers (= 0.75):

   Assume β = 0.95, C_L = 2.0 mg/L, and F = 1.0.

$$7000 \text{ kg/d} = \text{SOTR}\left[\frac{0.95(13.74) - 2.0}{9.08}\right](1.024^{20-20})(0.75)(1)$$

$$\text{SOTR} = 7{,}667 \text{ kg/d}$$

4. Estimate the air required.

   From Table 5-28, use the following oxygen transfer efficiency values

   Ceramic domes (grid pattern) = 27%

   Nonporous diffusers (dual spiral roll) = 12%

   From Appendix B, the density of air at 10°C and 1.0 atmosphere is:

$$\rho_{a,20^\circ C} = \frac{(1.01325 \times 10^5 \text{ N/m}^2)(28.97 \text{ kg/kg mole})}{= [8314 \text{ Nm/(kg mole air)}\bullet\text{K}]\,[(273.15 + 10)\text{K}]} = 1.247 \text{ kg/m}^3$$

   a. Air requirement for ceramic domes

$$\text{Air required} = \frac{(8985 \text{ kg/d})}{(1.247 \text{ kg/m}^3)(0.23)(0.27)} = 116{,}027 \text{ m}^3\text{/d}$$

   b. Air requirement for nonporous diffusers

$$\text{Air required} = \frac{(7667 \text{ kg/d})}{(1.247 \text{ kg/m}^3)(0.23)(0.12)} = 222{,}767 \text{ m}^3\text{/d}$$

5. Summer/winter operation

   Because there is about a 20 percent difference between the summer and winter air requirements, four blowers and a standby could used. During the winter operation, only three of the blowers would be used.