

Handbook of Environmental Engineering Problems

Chapter: Handbook of Environmental Engineering Problems

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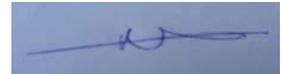
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Preface

We live at a time when no part of the natural environment is untouched by human activities. Although we have made great strides in addressing many of the natural resources and environmental problems caused by human activities, growth in the world population and rising standards of living continue to stress the natural environment and generate a spectrum of environmental problems that need to be addressed. Environmental engineers are called upon to understand, arrange, and manipulate the biological, chemical, ecological, economic, hydrological, physical, and social processes that take place in our environment in an effort to balance our material needs with the desire for sustainable environmental quality.

If an environmental engineer student, do not learn well, will not solve problems of environmental sciences in the future. Many engineer students learn all necessary lessons in university, but they cannot to answer to the problems or to pass the exams because of forgetfulness or lack of enough exercise. This book contains one hundred essential problems related to environmental engineering with a small volume. Undoubtedly, many problems can be added to the book but the authors tried to mention only more important problems and to prevent increasing volume of the book due to help to feature of portability of the book. To promotion of student skill, both SI and English system have been used in the problems and a list of important symbols has been added to the book. All of the problems solved completely. This book is useful for not only exercising and passing the university exams but also for use in actual project as a handbook. The handbook of environmental engineering problems is usable for agricultural, civil, chemical, energy and environmental students, teachers, experts, researchers, engineers, and designers. Prerequisite to study the book and to solve the problems is each appropriate book about environmental science, however, the authors recommends studying the References to better understanding of the problems and presented solutions. It is an honor for the authors to receive any review and suggestion to improve quality of the book.

Mohammad Valipour

A blue ink handwritten signature of Mohammad Valipour, consisting of a series of loops and a long horizontal stroke.

About Author



Mohammad Valipour is a Ph.D. candidate in Agricultural Engineering-Irrigation and Drainage at Sari Agricultural Sciences and Natural Resources University, Sari, Iran. He completed his B.Sc. Agricultural Engineering-Irrigation at Razi University, Kermanshah, Iran in 2006 and M.Sc. in Agricultural Engineering-Irrigation and Drainage at University of Tehran, Tehran, Iran in 2008. Number of his publications is more than 50. His current research interests are surface and pressurized irrigation, drainage engineering, relationship between energy and environment, agricultural water management, mathematical and computer modeling and optimization, water resources, hydrology, hydrogeology, hydro climatology, hydrometeorology, hydro informatics, hydrodynamics, hydraulics, fluid mechanics, and heat transfer in soil media.

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Abbreviations

A	- soil loss, tons/acre-year
A or a	- area, m ² or ft ²
A'	- surface area of the sand bed, m ² or ft ²
A _i	- acreage of subarea i, acres
A _L	- limiting area in a thickener, m ²
A _p	- surface area of the particles, m ² or ft ²
AA	- attainment area
amu	- atomic mass unit
B	- aquifer thickness, m or ft
BOD	- biochemical oxygen demand, mg/L
BOD ₅	- five day BOD
BOD _{ult}	- ultimate BOD: carbonaceous plus nitrogenous
Bq	- Becquerel: One radioactive disintegration per second
B	- slope of filtrate volume v/s time curve
b	- cyclone inlet width in m
C	- concentration of pollutant in g/m ³ or kg/m ³
C	- cover factor (dimensionless ratio)
C	- Hazen-Williams friction coefficient
C	- total percolation of rain into the soil, mm
C _d	- drag coefficient
C _i	- solids concentration at any level i
C _p	- specific heat at constant pressure in kJ/kg-K
C ₀	- influent solids concentration, mg/L
C _u	- underflow solids concentration, mg/L
Ci	- Curie; 3.7 × 10 ¹⁰ Bq
c	- Chezy coefficient
C	- wave velocity, m/s
cfs	- cubic feet per second
D (t)	- oxygen deficit at time (t), in mg/L.
D or d	- diameter, in m or ft or in.
D	- deficit in DO, in mg/L
D	- dilution (volume of sampled total volume) (Chap. 4)
D ₀	- initial DO deficit, in mg/L
DOT	- U.S. Department of Transportation
d	- depth of flow in a pipe, in m or in. (Chap. 7)
d'	- geometric mean diameter between sieve sizes, m or ft

- d_c - cut diameter, in m
- dB - decibel
- D_s - oxygen deficit upstream from wastewater discharge, mg/L
- D_p - oxygen deficit in wastewater effluent, mg/L
- E - rainfall energy, ft-tons/acre inch
- E - efficiency of materials separation
- E - evaporation, mm
- E - symbol for exponent sometimes used in place of 10.
- EPA - U.S. Environmental Protection Agency
- EQI - environmental quality index
- e - porosity fraction of open spaces in sand
- esu - electrostatic unit of charge
- eV - electron volt = 1.60×10^{-19} joule
- F - final BOD of sample, mg/L
- F - food (BOD), in mg/L
- f - friction factor
- G - flow in a thickener, $\text{kg}/\text{m}^2 \times \text{s}$
- G_L - limiting flux in a thickener, $\text{kg}/\text{m}^2 \times \text{s}$
- G - velocity gradient, in s^{-1}
- Gy - gray: unit of absorbed energy; 1 joule/kg
- g - acceleration due to gravity, in m/s^2 or ft/s^2
- H or h - height, m
- H - depth of stream flow, in m
- H - effective stack height, m
- H - total head, m or ft
- H_L - total head loss through a filter, m or ft
- Hz - Hertz, cycles/s
- h - geometric stack elevation, m
- h - fraction of BOD not removed in the primary clarifier
- h - depth of landfill, m
- h_d - net discharge head, m or ft
- h_L - head loss, m or ft
- h_s - net static suction head, m or ft
- i - fraction of BOD not removed in the biological treatment step
- j - fractions of solids not destroyed in digestion
- J - Pielov's equitability index
- K - soil erodibility factor, ton/acre/R unit
- K - proportionality constant for minor losses, dimensionless

- K_p - coefficient of permeability, m^3/day or gal/day
- K_T - fraction of atoms that disintegrate per second= $0.693/t_{0.5}$
- k - fraction of influent SS removed in the primary clarifier
- K_s - saturation constant, in mg/L
- kW - kilowatts
- kWh - kilowatt-hours
- L - depth of filter, m or ft
- L or l - length, m or ft
- LS - topographic factor (dimensionless ratio)
- L_o - ultimate carbonaceous oxygen demand, in mg/L
- L_1 - length of cylinder in a cyclone, in m
- L_2 - length of cone in a cyclone, in m
- L_F - feed particle size, 80% finer than, μm
- L_s - ultimate BOD upstream from wastewater discharge, mg/L
- L_p - product size, 80% finer than, μm
- L_p - ultimate BOD in wastewater effluent, mg/L
- L_x - x percent of the time stated sound level (L) was exceeded, percentage
- LAER - lowest achievable emission rate
- LCF - latent cancer fatalities
- LD_{50} - lethal dose, at which 50% of the subjects are killed
- LDC_{50} - lethal dose concentration at which 50% of the subjects are killed
- LET - linear energy transfer
- M - mass of a radionuclide, in g
- M - microorganisms (SS), in mg/L
- MACT - maximum achievable control technology
- MeV - million electron volts
- MLSS - mixed liquor suspended solids, in mg/L
- MSS - moving source standards
- MSW - municipal solid waste
- MW_e - megawatts (electrical); generating plant output
- MW_t - megawatts (thermal); generating plant input
- m - mass, in kg
- m - rank assigned to events (e.g., low flows)
- N - number of leads in a scroll centrifuge
- N - effective number of turns in a cyclone
- N^0 - Avogadro's number, 6.02×10^{23} atoms/g-atomic weight
- NAA - non-attainment areas
- NAAQS- National Ambient Air Quality Standards

- NEPA - National Environmental Policy Act
- NPDES - National Pollution Discharge Elimination System
- NPL - noise pollution level
- NPSH - net positive suction head, m or ft
- NRC - Nuclear Regulatory Commission
- NSPS - new (stationary) source performance standards
- n - number of events (e.g., years in low flow records)
- n - Manning roughness coefficient
- n - revolutions per minute
- n - number of subareas identified in a region
- n_c - critical speed of a trommel, rotations/s
- n_i - number of individuals in species i
- OCS - Outer Continental Shelf
- OSHA - Occupational Safety and Health Administration
- P - erosion control practice factor (dimensionless ratio)
- P - phosphorus, in mg/L
- P - power, N/s or ft-lb/s
- P - precipitation, mm
- P - pressure, kg/m² or lb/ft² or N/m² or atm
- ΔP - pressure drop, in m of water
- P_{ref} - reference pressure, N/m²
- P_s - purity of a product x, %
- PIU - parameter importance units
- PMN - pre-manufacture notification
- POTW - publicly owned (wastewater) treatment works
- PPBS - planning, programming, and budgeting system
- PSD - prevention of significant deterioration
- Q or q - flow rate, in m³/s or gal/min
- Q - emission rate, in g/s or kg/s
- Q - number of Ci or Bq
- Q_h - heat emission rate, kJ/s
- Q_o - influent flow rate, m³/s
- Q_p - pollutant flow, in mgd or m³/s
- Q_p - flow rate of wastewater effluent, m³/s
- Q_s - Stream flow, in mgd or m³/s
- Q_s - Flow rate upstream from wastewater discharge, m³/s
- Q_w - waste sludge flow rate, in m³/s

- q - Substrate removal velocity, in s^{-1}
- R - radius of influence of a gas withdrawal well, m
- R - Rainfall factor
- R - recovery of pollutant or collection efficiency, 5%
- R - % of overall recovery of, SS in settling tank
- R or r - hydraulic radius, in m or ft
- R - runoff coefficient
- R_x - recovery of a product x, %
- R - Reynolds number
- RACT - reasonable achievable control technology
- RCRA - Resource Conservation and Recovery Act
- RDF - refuses derived fuel
- ROD - record of decision
- r - radius, in m or ft or cm
- r - hydraulic radius in Hazen-Williams equation, m or ft
- r - specific resistance to filtration, m/kg
- rad - unit of absorbed energy: 1 erg/g
- rem - roentgen equivalent man
- S - rainfall storage, mm
- S - scroll pitch, m
- S - substrate concentration, estimated as BOD, mg/L
- S_o - influent BOD, kg/h
- S_d - sediment delivery ratio (dimensionless factor)
- S_o - influent substrate concentration estimated as BOD, mg/L
- SIP - State Implementation Plans
- SIU - significant individual user
- SIW - significant individual waste
- SL - sound level
- SPL - sound pressure level
- SS - suspended solids, in mg/L
- S_v - sievert; unit of dose equivalent
- SVI - sludge volume index
- s - hydraulic gradient
- s - slope
- s - sensation (hearing, touch, etc.)
- T - temperature, in $^{\circ}C$
- TOSCA - ToxicSubstances Control Act
- TRU - transuranic material or transuranic waste

- t - time, in s or days
- t_c - critical time, time when minimum DO occurs, in s
- $t_{0.5}$ - radiological half-life of a radionuclide
- t - time of flocculation, in min
- t - retention time, in s or days
- UC - unclassifiable (inadequate information)
- USDA - U.S. Department of Agriculture
- USLE - universal soil loss equation
- USPHS - U.S. Public Health Service
- u - average wind speed, m/s
- V - volume, in m^3 or ft^3
- V_p - volume occupied by each particle, in m^3 or ft^3
- v - interface velocity at solids concentration C_i
- v - velocity of flow, m/s or ft/s, and superficial velocity, m/day or ft/day
- v - velocity of the paddle relative to the fluid, m/s or ft/s
- v - velocity of water through the sand bed, d s or ft/s
- v_a - velocity of water approaching sand, m/s or ft/s
- v_d - drift velocity, m/s
- v_i - inlet gas velocity, m/s
- v_o - settling velocity of a critical particle, in m/s
- v_p - velocity in a partially full pipe, m/s or ft/s
- v_R - radial velocity, m/s
- v_s - settling velocity of any particle, in m/s
- v' - actual water velocity in soil pores, m/day or ft/day
- V - filtrate volume, m^3
- w - specific weight, kg/m^3 or lb/ft^3
- WHP - water horsepower
- WEPA - Wisconsin Environment Policy Act
- WPDES- Wisconsin Pollutant Discharge Elimination System
- W - power level, watts
- w - cake deposited per volume of filtrate, kg/m^3
- W - specific energy, kWh/ton
- W_i - Bond work index, kWh/ton
- X - seeded dilution water in sample bottle, mL
- x - weight fraction of particles retained between two sieves
- X_e - effluent SS, mg/L
- X_o - influent SS, kg/h

- X - microorganism concentration, estimated as SS, mg/L
 X_e - effluent microorganism concentration, estimated as SS, mg/L
 X_r - return sludge microorganism concentration, estimated as SS, mg/L
 X_0 - influent microorganism concentration, estimated as SS, mg/L
 x - particle size, m
 x_c - characteristic particle size, m
 x_0, y_0 - mass per time of feed to a materials separation device
 x_1, y_1 - mass per time of components x and y exiting from a materials separation device through exit stream 1
 x_2, y_2 - mass per time of components x and y exiting from a materials separation device through exit stream 2
 x_1 - mass of pollutant that could have been captured, kg
 x_2 - mass of pollutant that escaped capture, kg
 x_0 - mass of pollutant collected, kg
 x - thickness, in m
 Y - yield
 Y - yield, kg SS produced/kg BOD used
 Y - cumulative fraction of particles (by weight) less than some specific size
 Y - volume of BOD bottle, mL
 Y_F - filter yield, kg/m²-s
 y - oxygen used (or BOD) at time t , in mg/L
 Z - elevation, m or ft
 z - depth of sludge in a bowl, m
 $z(t)$ - oxygen required for decomposition, in mg/L
 Σ - sigma factor
 α - alpha radiation
 β - beta factor
 β - Beta radiation
 γ - gamma radiation
 γ - kinematic viscosity, cm²/s
 ΔS - net BOD utilized in secondary treatment, kg/h
 ΔX - net solids produced by the biological step, kg/h
 η - plastic viscosity, N-s/m²
 $\Delta\omega$ - difference between bowl and conveyor rotational speed, rad/s
 Θ_c - mean cell residence time, or sludge age, days
 η - pump efficiency
 λ - wavelength, m
 μ - viscosity, in N-s/m² or poise (lb-s/ft²)

- μ - growth rate constant, in s^{-1}
- μ - Maximum growth rate constant, in s^{-1}
- ν - frequency of sound wave, cycle/s
- φ - shape factor
- ρ - density, g/cm, kg/cm^3 , lb-s/ft⁴ or lb-s²/ft³
- ρ_s - density of a solid, in kg/m^3
- σ_y - standard deviation, y direction, m
- σ_z - standard deviation, z direction, m
- τ - shear stress, N/m^2
- τ_y - yield stress, N/m^2
- ω - rotational velocity, rads

Handbook of Environmental Engineering Problems

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Problems

1. Calculate the storm water flow from a catchment area, given that:

Rain intensity (R)=50 mm/h Area (A)=54 hectares and

30% of area consists of roof with runoff rate as 0.9,

30% of area consists of open field with runoff rate as 0.2,

40% of area consists of roads with runoff rate as 0.4.

$$\text{Runoff rate} = \frac{0.30 \times 0.9 + 0.30 \times 0.2 + 0.40 \times 0.4}{0.3 + 0.3 + 0.4} = 0.49$$

$$\text{Storm water flow } Q = \frac{AIR}{360} = \frac{54 \times 0.49 \times 50}{360} = 3.675 \text{ m}^3 / \text{s}$$

2. Determine the velocity of flow and discharge (flowing full) in a sewer, given that, diameter of sewer is 60 cm and Slope, 1/500 or 0.002.

Find the change in velocity if the flow is half full.

(i) Using Chezy's formula, we have $V = 60 \sqrt{\left(\frac{0.60}{4}\right)(0.002)} = 1.04 \text{ m/s}$

and $Q = \pi \frac{(0.6)^2}{4} \times 1.04 = 0.28 \text{ m}^3 / \text{s}$

(ii) Using Manning's formula, $V = \frac{1}{0.013} \left(\frac{0.60}{4}\right)^{2/3} (0.002)^{1/2} = 0.86 \text{ m/s}$

$Q = \pi \frac{(0.60)^2}{4} \times 0.86 = 0.24 \text{ m}^3 / \text{s}$

(iii) Using Hazen William's formula, $V = 85 \left(\frac{0.60}{4}\right)^{0.63} (0.002)^{0.54} = 0.89 \text{ m/s}$

$$Q = \pi \frac{(0.60)^2}{4} \times 0.89 = 0.25 \text{ m}^3 / \text{s}$$

(iv) If $d/D=0.5$; $v/V=1$ and $q/Q=0.5$; hence the result

3. Determine the slope and diameter of a sewer, if $Q=1500 \text{ L/s}$ and $V=1.5 \text{ m/s}$.

$$\text{Cross sectional area} = \frac{\pi d^2}{4} = \frac{Q}{V} = \frac{1.5}{1.5} = 1 \text{ m}^2$$

$$d = \sqrt{\frac{4}{\pi} \times 1} = 1.12 \text{ m}$$

Using Chezy's formula,

$$1.5 = 50 \sqrt{\frac{1.12}{4}} \times s$$

$$\text{Slope} = 0.0032$$

4. Calculate the diameter and discharge of a circular sewer laid at a slope of 1 in 400 when it is running half full and with a velocity of 1.9 m/s.

Using Manning's formula, we have

$$1.9 = \frac{1}{0.012} \left(\frac{d}{4} \right)^{2/3} \times \frac{1}{\sqrt{400}}$$

$$\text{Or } d = 1.23 \text{ m}$$

$$\text{Discharge} = \pi \times \frac{1.23^2}{2 \times 4} \times 1.9 = 1.13 \text{ m}^3 / \text{s}$$

5. Determine the diameter and the velocity of flow, if $Q=0.5 \text{ m}^3/\text{s}$, and $s=1/500$

According to Darcy - Weisbach head loss formula

$$\text{Slope} = h / L = \frac{fV^2}{2gd} = \frac{1}{500} = 0.002$$

i.e.,

$$(i) \frac{V^2}{d} = \frac{2g \times 0.002}{0.01} = 3.91$$

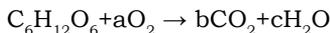
$$(ii) \text{ Further, } Q = AV = \frac{\pi d^2}{4} V, \text{ or, } Vd^2 = \frac{4Q}{\pi} = \frac{4 \times 0.5}{\pi} = 0.64$$

Solving (i) and (ii) we have

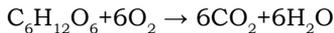
$$V = 1.73 \text{ m/s and } d = 0.76 \text{ cm}$$

6. What is the theoretical oxygen demand in mg/L for a 1.67×10^{-3} molar solution of glucose, $C_6H_{12}O_6$ to decompose completely?

First balance the decomposition reaction (which is an algebra exercise):



As



This is, for every mole of glucose decomposed, 6 mol of oxygen are required. This gives us a constant to use change moles per liter of glucose to milligrams per liter of O_2 required, a (relatively) simple unit conversion.

$$\left[\frac{1.67 \times 10^{-3} \text{ mol glucose}}{L} \right] \times \left[\frac{6 \text{ mol of } O_2}{\text{mol glucose}} \right] \times \left[\frac{32 \text{ g } O_2}{\text{mol } O_2} \right] \times \left[\frac{1000 \text{ mg}}{g} \right] = 321 \frac{\text{mg } O_2}{L}$$

7. What is the theoretical oxygen demand in liters of air for a 300 mg/L solution of methylamine, CH_3NH_2 , to decompose completely?

The first step is to balance the decomposition reaction:



As

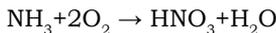


That is, for every mole of methylamine decomposed, 1.5 mol of oxygen are required for the C-ThOD.

$$C - ThoD = \left[\frac{300 \text{ mg } CH_3N}{L} \right] \times \left[\frac{g}{1000 \text{ mg}} \right] \times \left[\frac{\text{mol } CH_3N}{31.058 \text{ g } CH_3N} \right] \times \left[\frac{1.5 \text{ mol of } O_2}{\text{mol } CH_3N} \right] \\ \times \left[\frac{22.4 \text{ L } O_2}{\text{mol } O_2} \right] \times \left[\frac{L \text{ air}}{0.21 \text{ L } O_2} \right]$$

$$C - ThoD \cong 1.55$$

But the NH_3 will also use O_2 :



So there will be an N-ThOD.

$$N - ThoD = \left[\frac{300 \text{ mg } CH_3N}{L} \right] \times \left[\frac{g}{1000 \text{ mg}} \right] \times \left[\frac{\text{mol } CH_3N}{31.058 \text{ g } CH_3N} \right] \times \left[\frac{1 \text{ mol of } NH_3}{\text{mol } CH_3N} \right] \times \left[\frac{2 \text{ mol } O_2}{\text{mol } NH_3} \right] \\ \times \left[\frac{22.4 \text{ L } O_2}{\text{mol } O_2} \right] \times \left[\frac{L \text{ air}}{0.21 \text{ L } O_2} \right] \cong 2.06 \frac{L \text{ air}}{L \text{ solution}}$$

So the total theoretical oxygen demand is:

$$ThOD = C - ThoD + N - ThoD = 1.55 + 2.06 = 3.6 \text{ L air per L solution.}$$

8. What is the theoretical oxygen demand in liters of air for a 50 mg/L solution of acetone, CH_3COCH_3 , to decompose completely?

The first step is, again, to balance the decomposition reaction:



As



That is, for every mole of acetone decomposed, 4 mol of oxygen are required. Use the ideal gas law and the percent oxygen by volume in air to calculate the liters of air required.

$$\left[\frac{50 \text{ mg acetone}}{L} \right] \times \left[\frac{g}{1000 \text{ mg}} \right] \times \left[\frac{\text{mol acetone}}{58.08 \text{ g acetone}} \right] \times \left[\frac{4 \text{ mol of } O_2}{\text{mol acetone}} \right] \\ \times \left[\frac{22.4 \text{ L } O_2}{\text{mol } O_2} \right] \times \left[\frac{l \text{ air}}{0.21 \text{ L } O_2} \right] \cong 0.4 \frac{L \text{ air}}{L \text{ solution}}$$

9. Calculate the BOD₅ if the temperature of the sample and seeded dilution water are 20°C (saturation is 9.07 mg/L), the initial Dos are saturation, and the sample dilution is 1:30 with seeded dilution water. The final DO of the seeded dilution water is 8 mg/L, and the final DO of the sample and seeded dilution water is 2 mg/L. Recall that the volume of a BOD bottle is 300 mL.

$$D = \frac{30 \text{ mL}}{V_s}$$

Therefore

$$V_s = 10 \text{ mL and } X = 300 \text{ mL} - 10 \text{ mL} = 290 \text{ mL}$$

$$BOD_5 = \left[(9.07 \text{ mg/L} - 2 \text{ mg/L}) - (9.07 \text{ mg/L} - 8 \text{ mg/L}) \left(\frac{290 \text{ mL}}{300 \text{ mL}} \right) \right] 30 = 181 \text{ mg/L}$$

10. Assuming a deoxygenating constant of 0.25 d⁻¹, calculate the expected BOD₅ if the BOD₃ is 148 mg/L.

$$148 \text{ mg/L} = L \left[1 - e^{-(0.25 \text{ d}^{-1})(3 \text{ d})} \right] \rightarrow L = 280 \text{ mg/L}$$

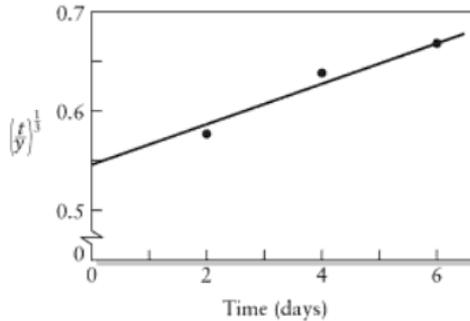
$$y_5 = (280 \text{ mg/L}) \left[1 - e^{-(0.25 \text{ d}^{-1})(5 \text{ d})} \right] = 200 \text{ mg/L}$$

11. The BOD versus time data for the first five days of a BOD test are obtained as follows:

Time, t (days)	BOD, y (mg/L)
2	10
4	16
6	20

Calculate k₁ and L.

From the graph, the intercept is b=0.545 and the slope is m=0.21. Thus



$$k_1 = 6 \left(\frac{0.021}{0.545} \right) = 0.23 \text{ d}^{-1}$$

$$L = \frac{1}{6(0.021)(0.545)^2} = 27 \text{ mg / L}$$

12. A laboratory runs a solids test. The weight of the crucible=48.6212 g. A 100-mL sample is placed in the crucible and the water is evaporated. The weight of the crucible and dry solids=48.6432 g. The crucible is placed in a 600 °C furnace for 24 hr and cooled in desiccators. The weight of the cooled crucible and residue, or unburned solids,=48.6300 g. Find the total, volatile, and fixed solids.

$$TS = \frac{(48.6432 \text{ g}) - (48.6212 \text{ g})}{100 \text{ mL}} \times 10^6 = 220 \text{ mg / L}$$

$$FS = \frac{(48.6300 \text{ g}) - (48.6212 \text{ g})}{100 \text{ mL}} \times 10^6 = 88 \text{ mg / L}$$

$$VS = 220 - 88 = 132 \text{ mg/L}$$

13. The EPA has calculated that unit lifetime risk from exposure to Ethylene Dibromide (EDB) in drinking water is 0.85 LFC per 10⁵ persons. What risk is experienced by drinking water with an average EDB concentration of 5 pg/L for five years?

The risk may be estimated using either unit annual risk or unit lifetime risk. Since the unit lifetime risk is given, we may write

$$\text{Risk} = \frac{(5 \times 10^{-12} \text{ g / L})(0.85 \text{ LCF})(5 \text{ yrs})}{(10^5)(10^{-9} \text{ g / L})(70 \text{ yrs})} = 3.0 \times 10^{-9} \text{ LCF}$$

The estimated risk is that about three fatal cancers would be expected in a population of a billion people who drink water containing 5 pg/L EDB for five years. Although there is a popular tendency to translate this to an “individual risk” of “a change of three in a billion of having a fatal cancer,” this statement of risk is less meaningful than the statement of population risk.

14. Assume that a large stream has a reoxygenation constant k_2 of 0.4/day, a flow velocity of 5 miles/h, and at the point of pollutant discharge, the stream is saturated with oxygen at 10 mg/L. The wastewater flow rate is very small compared with the

stream flow, so the mixture is assumed to be saturated with dissolved oxygen and to have an oxygen demand of 20 mg/L. The deoxygenating constant k_1' is 0.2/day. What is the dissolved oxygen level 30 miles downstream?

Stream velocity=5 miles/h, hence it takes 30/5 or 6 h to travel 30 miles.

Therefore, $t=6 \text{ h}/24 \text{ h/day}=0.25 \text{ day}$,

And $D_0=0$ because the stream is saturated.

$$D = \frac{(0.2)(20)}{0.4 - 0.2} \left(e^{-(0.2)(0.25)} - e^{-(0.4)(0.25)} \right) = 1.0 \text{ mg / L}$$

The dissolved oxygen 30 miles downstream will be the saturation level minus the deficit, or $10-1.0=9.0 \text{ mg/L}$.

15. Calculate the BOD_5 of a water sample, given the following data:

Temperature of sample=20 °C (dissolved oxygen saturation at 20 °C is 9.2 mg/L,

Initial dissolved oxygen is saturation,

Dilution is 1:30, with seeded dilution water,

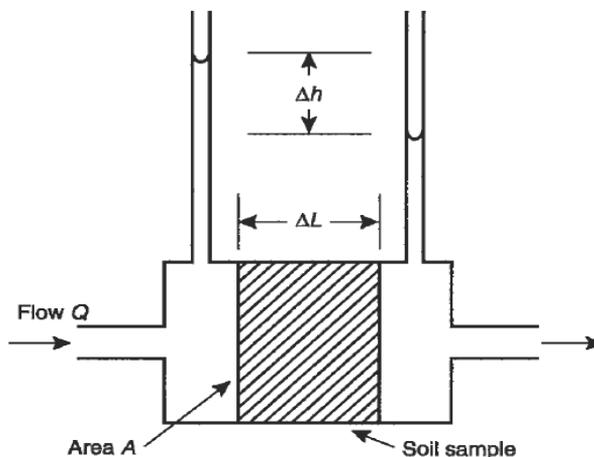
Final dissolved oxygen of seeded dilution water is 8 mg/L,

Final dissolved oxygen bottle with sample and seeded dilution water is 2 mg/L, And

Volume of BOD bottle is 300mL.

$$BOD_5 = \frac{(9.2 - 2) - (9.2 - 8)(290 / 300)}{0.033} = 183 \text{ mg / L}$$

16. A soil sample is installed in a permeameter as shown in the figure. The length of the sample is 0.151 m, and it has a cross-sectional area of 0.05 m². The water pressure placed on the sample is 2 m, and a flow rate of 2.0 m³/day is observed. What is the coefficient of permeability?



$$K = \frac{Q}{A(\Delta h / \Delta L)} = \frac{2.0}{0.05 \times (2 / 0.1)} = 2 \text{ m}^3 / \text{m}^2 - \text{day}$$

17. A confined aquifer is 6 m deep and the coefficient of permeability in the soil is $2\text{m}^3/\text{day}\cdot\text{m}^2$. The wells are 100 m apart, and the difference in the water elevation in the wells is 3.0 m. Find the flow rate and the superficial velocity through the aquifer.

The slope of the pressure gradient, $\Delta h/\Delta L=3/100=0.03$, and the flow rate for a section of aquifer 1 m wide is

$$Q = KA \frac{\Delta h}{\Delta L} = 2 \times 6 \times 0.03 = 0.36 \text{ m}^3 / \text{day}$$

The superficial velocity is

$$v = \frac{Q}{A} = \frac{0.36}{1 \times 6} = 0.06 \text{ m} / \text{day}$$

18. A well is 0.2 m in diameter and pumps from an unconfined aquifer 30 m deep at an equilibrium (steady-state) rate of 1000m^3 per day. Two observation wells are located at distances 50 and 100m, and they have been drawn down by 0.2 and 0.3 m, respectively. What is the coefficient of permeability and estimated drawdown at the well?

$$K = \frac{Q \ln(r_1 / r_2)}{\pi(h_1^2 - h_2^2)} = \frac{1000 \ln(100 / 50)}{\pi[(29.8)^2 - (29.7)^2]} = 37.1 \text{ m}^3 / \text{m}^2 - \text{day}$$

Now if the radius of the well is assumed to be $0.2/2=0.1$ m, this can be plugged into the same equation, as

$$Q = \frac{\pi K (h_1^2 - h_2^2)}{\ln(r_1 / r_2)} = \frac{\pi \times 37.1 \times [(27)^2 - h_2^2]}{\ln(50 / 0.1)} = 1000$$

And solving for h_2 ,

$$h_2 = 28.8 \text{ m}$$

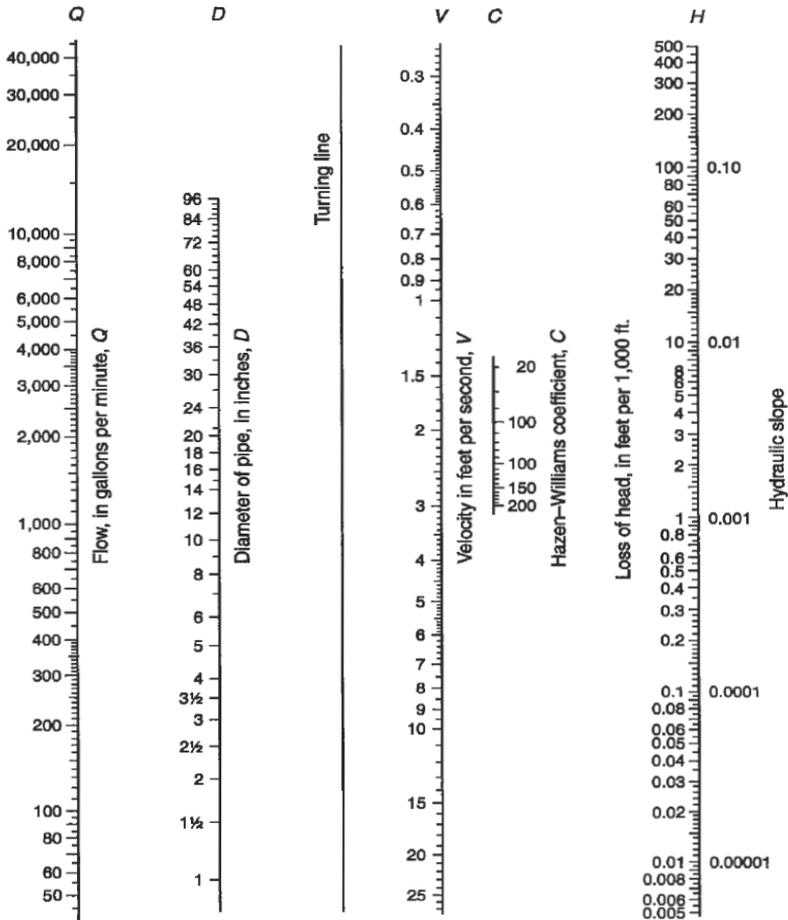
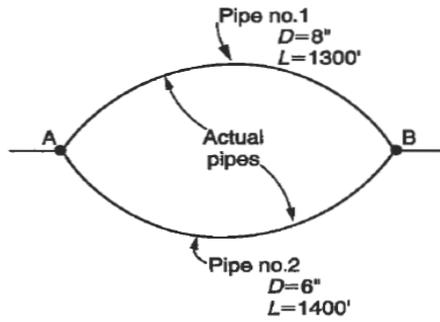
Since the aquifer is 30 m deep, the drawdown at well is $30-28.8=1.2$ m

19. The loss for a flow of 1.0 cfs through a given 6-in. main with a gate valve wide open is 20 ft. Find the head loss with the gate valve 75% closed ($K=24.0$).

$$v = \frac{Q}{A} = \frac{1.0}{0.2} = 5 \text{ ft} / \text{s}$$

$$h_L = h_0 + K \frac{v^2}{2g} = 20 + 24 \left(\frac{5^2}{64.4} \right) = 29.2 \text{ ft}$$

20. For the parallel pipes as shown in the figure, find the diameter of equivalent pipe (length is assumed to be 1000 ft) using the nomograph



1. Loss of head through pipe 1 must always equal loss of head through pipe 2 between points A and B.

2. Assume any arbitrary head loss, say 10 ft.

3. Calculate head loss in feet per 1000 ft for pipes 1 and 2.

Pipe 1: $(10/1300) \times (1000) = 7.7 \text{ ft}/1000 \text{ ft}$

Pipe 2: $(10/1400) \times (1000) = 7.1 \text{ ft}/1000 \text{ ft}$.

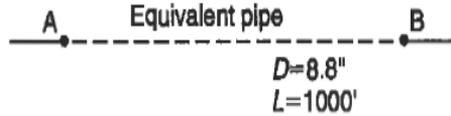
4. Use the nomograph to find flow in gallons per minute (gpm).

Pipe 1: $D=8$ in., $s=0.0077$, $Q=495$ gpm

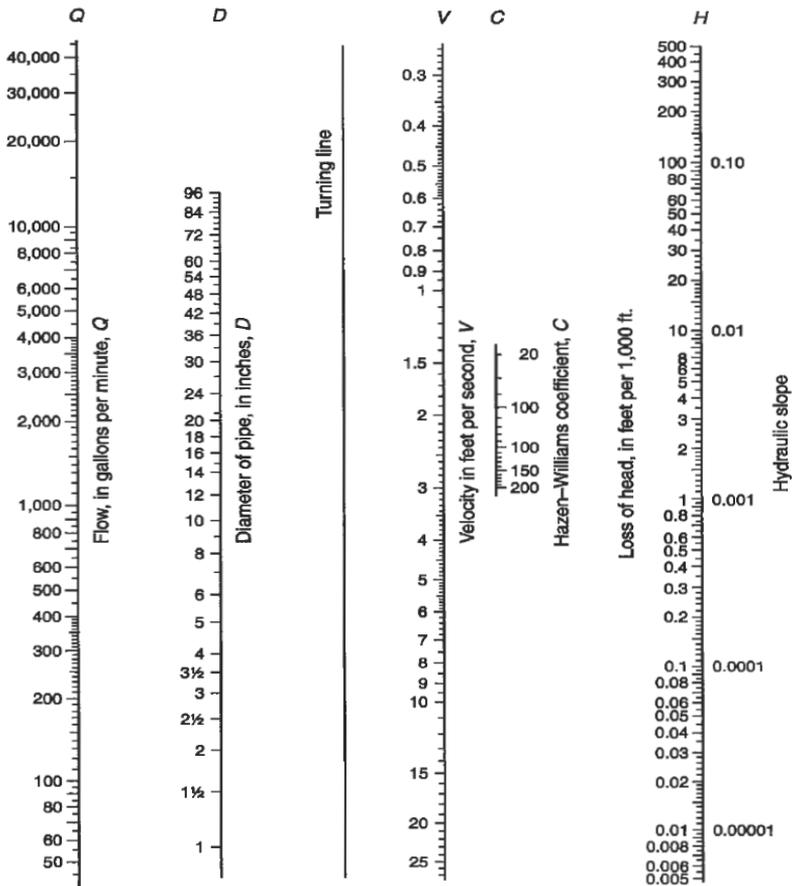
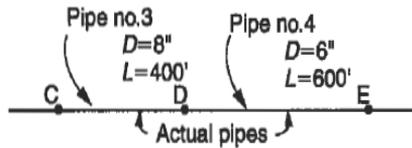
Pipe 2: $D=6$ in., $s=0.0071$, $Q=220$ gpm

Total Q through both pipes= 715 gpm.

5. Using the nomograph with $s=0.010$ and $Q=715$ gpm, equivalent pipe size is found to be 8.8 in. in diameter.



21. For the pipes in series as shown in the figure, find the diameter of equivalent pipe (length is assumed to be 1000 ft) using the nomograph.



Quantity of water flowing through pipes 3 and 4 is the same.

Assume any arbitrary flow through pipes 3 and 4, say 500 gm.

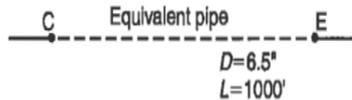
Using the nomograph, find head loss for pipes 3 and 4.

Pipe 3: $D=8$ in., $L=400$ ft, $Q=500$ gpm, $h'=s_1 \times L_1=0.008 \times 400=3.2$ ft

Pipe 4: $D=6$ in., $L=600$ ft, $Q=500$ gpm, $h'=s_1 \times L_1=0.028 \times 600=16.8$ ft

Total head loss in both pipes=20 ft.

Using the nomograph with head loss=20 ft, $s=20/1000$, and $Q=500$ gpm, equivalent pipe size is found to be 6.5 in. in diameter.



22. A water treatment plant is designed for 30 million gallons per day (mgd). The flocculator dimensions are length=100 ft, width=50 ft, depth=16 ft. Revolving paddles attached to four horizontal shafts rotate at 1.7 rpm. Each shaft supports four paddles that are 6 in. wide and 48 in. long. Paddles are centered 6 ft from the shaft. Assume $C_p=1.9$ and the mean velocity of water is 35% of the paddle velocity. Find the velocity differential between the paddles and the water. At 50 of, the density of water is $1.94 \text{ lb-s}^2/\text{ft}^3$ and the viscosity is $2.73 \times \text{lb-s}/\text{ft}^2$. Calculate the value of G and the time of flocculation (hydraulic retention time).

The rotational velocity is

$$v_r = \frac{2\pi m}{60}$$

$$v_r = \frac{(2\pi)(6)(1.7)}{60} = 1.07 \text{ ft/s}$$

The velocity differential between paddles and fluid is assumed to be 65% of v_r , so that

$$v = 0.65v_r = (0.65)(1.7) = 0.70 \text{ ft/s}$$

$$P = \frac{(1.9)(16)(0.5 \text{ ft})(48 \text{ ft})(1.94 \text{ lb-s}^2/\text{ft}^3)(0.70 \text{ ft/s})^3}{2} = 243 \text{ ft-lb/s}$$

$$G = \sqrt{\left(\frac{243}{(100)(50)(16)(2.73 \times 10^{-5})} \right)} = 10.5 \frac{\text{ft/s}}{\text{ft}}$$

This is a little low. The time of flocculation is

$$\bar{t} = \frac{V}{Q} = \frac{(100)(50)(16)(7.48)(24)(60)}{(30)10^5} = 28.7 \text{ min}$$

So that the Gt value is 1.8×10^4 . This is within the accepted range.

23. A sand consisting of the following sizes is used

Seive number	5 of sand retained on sieve x 10 ²	Geometric mean sand size, ft x 10 ⁻³
14-20	1.10	3.28

20-28	6.60	2.29
28-32	15.94	1.77
32-35	18.60	1.51
35-42	19.10	1.25
42-48	17.60	1.05
48-60	14.30	0.88
60-65	5.10	0.75
65-100	1.66	0.59

The filter bed measures 20 × 20 ft² and is 2 ft deep. The sand has a porosity of 0.40 and a shape factor of 0.95. The filtration rate is 4 gal/min-ft². Assume the viscosity is 3 × 10⁻⁵ lb-s/ft². Find the head loss through the clean sand.

The solution is shown in tabular form:

Reynolds number, R	Friction factor, f	x/d	F(x/d)
1.80	51.7	3.4	174
1.37	67.4	28.8	1,941
1.06	86.6	90.1	7,802
0.91	100.6	123.2	12,394
0.75	121.7	152.8	18,595
0.63	144.6	167.6	24,235
0.53	171.5	162.5	27,868
0.45	201.7	68.0	13,715
0.35	258.8	28.1	7,272

Column 1: The approach velocity is

$$v_a = 4 \left(\frac{\text{gal}}{\text{min-ft}^2} \right) \left(\frac{1 \text{ ft}^3}{7.481 \text{ gal}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right) = 8.9 \times 10^{-3} \text{ ft/s}$$

For the first particle size, $d = 3.28 \times 10^{-3}$ ft, and

$$R = \frac{(0.95)(1.94)(89)(10^{-3})(3.28)(10^{-3})}{3 \times 10^{-5}} = 1.80$$

Column 2:

$$f = 150 \left(\frac{1-0.4}{1.8} \right) + 1.75 = 51.75$$

Columns 3 and 4: For the first size, $x = 1.10\%$ and $d = 3.28 \times 10^{-3}$

$$f \frac{x}{d} = \frac{(51.75)(0.011)}{3.28 \times 10^{-3}} = 174$$

The last column is summed: $\Sigma f(x/d) = 113,977$, we have

$$h_L = \frac{2}{0.95} \left(\frac{1-0.4}{(0.4)^3} \right) \left(\frac{(8.9 \times 10^{-3})^2}{32.2} \right) (113,977) = 5.78 \text{ ft}$$

24. An 8-in.-diameter cast iron sewer is to be set at a grade of 1-m fall per 500-m length. What will be the flow in this sewer when it is flowing full (use the table)?

Type of channel, closed conduits	Roughness coefficient n
Cast iron	0.013
Concrete, Straight	0.011
Concrete, with bends	0.013
Concrete, unfinished	0.014
Clay, vitrified	0.012
Corrugated metal	0.024
Brickwork	0.013
Sanitary sewers coated with slime	0.013

$$v = \frac{1.486}{0.013} \left[\frac{\pi(8/12)^2}{4} \right]^{2/3} \left[\frac{1}{500} \right]^{1/2} = 1.54 \text{ ft/s}$$

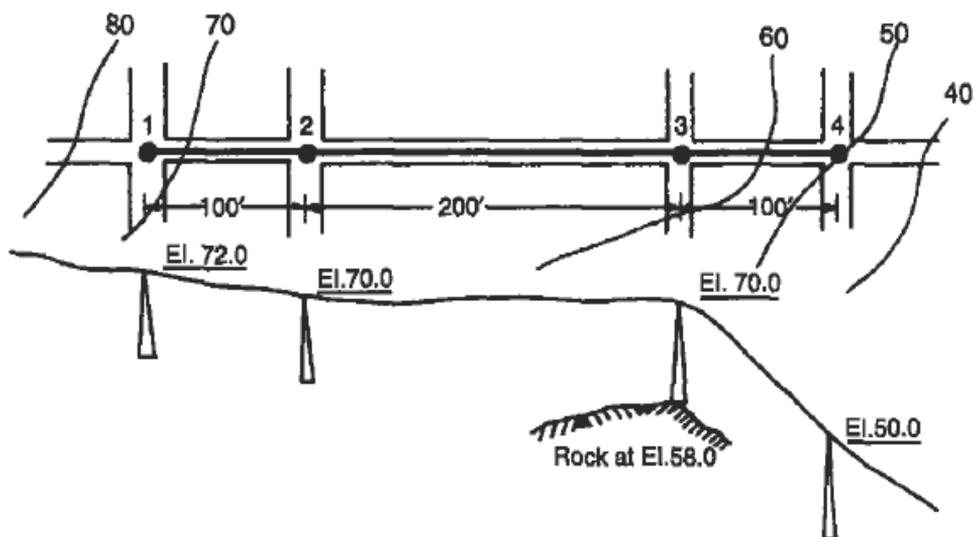
Using English units and noting that n=0.013 from the table,

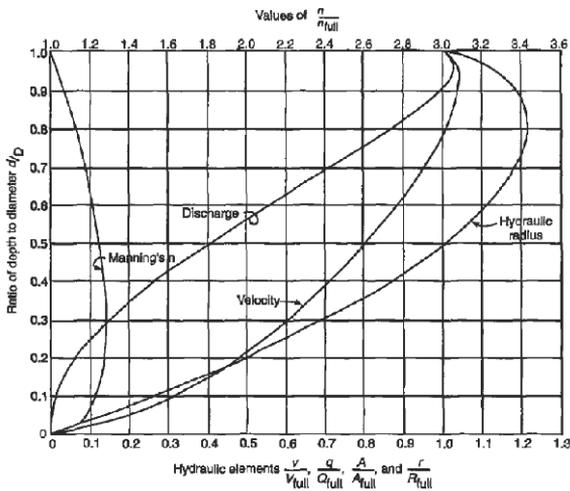
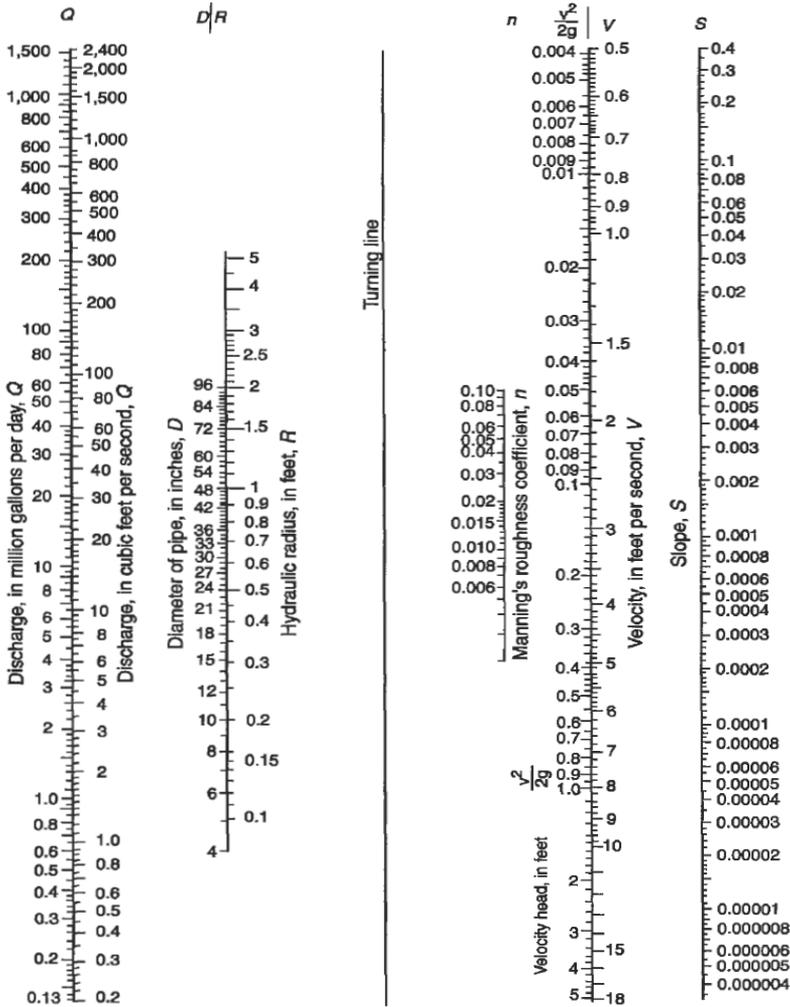
$$A = \frac{\pi(8/12)^2}{4} = 0.35 \text{ ft}^2$$

And since the area is

$$Q = Av = (0.35)(1.54) = 0.54 \text{ cfs}$$

25. The system shown in the figure is to be designed given the following flows: maximum flow=3.2 mgd, minimum flow=0.2 mgd, minimum allowable velocity=2 ft/s, and maximum allowable velocity=12 ft/s. All manholes should be about 10 ft deep, and there is no additional flow between Manhole 1 and Manhole 4. Design acceptable invert elevations for this system. (Use the graphs.)





From Manhole 1 to Manhole 2:

1. The street slopes at 2/100, so choose the slope of the sewer $s=0.02$.
2. Assume $n=0.013$ and try $D=12$ in. From the nomograph, connect $n=0.013$ and $s=0.02$, and extend that straight line to the turning line.
3. Connect the point on the turning line with $D=12$ in.
4. Read $v=6.1$ ft/s for $Q=3.2$ mgd from intersection of the line drawn in Step 3. This is acceptable for the sewer flowing full.
5. To check for minimum velocity,

$$q/Q=0.2/3.2=0.063,$$

And from the hydraulic elements chart, $q/Q=0.063$ intersects the discharge curve at $d/D=0.2$, which intersects the velocity curve at $v_p/v=0.48$, and

$$v_p=0.48(6.1\text{ ft/s})=2.9\text{ ft/s}$$

6. The downstream invert elevation of Manhole 1 is ground elevation minus 10 ft, or 62.0 ft. The upstream invert elevation of Manhole 2 is thus $62.0 - 2.0=60.0$ ft. Allowing 0.1 ft for head loss in the manhole, the downstream invert elevation is 59.9 ft.

From Manhole 2 to Manhole 3, the slope will be a problem because of rock. Try a larger pipe, $D=18$ in. Repeating steps 1 and 2,

7. Connect the point on the turning line with $D=18$ in.

8. From the nomograph, $v=2.75$ ft/s for $Q=3.2$ mgd, $v_p/v=0.48$ and

$$v_p=0.48(2.75\text{ ft/s})=1.32\text{ ft/s}.$$

Even with a slope of 0.002 (from the nomograph), the resulting velocity at minimum flow is too low. Try $s=0.005$ with $D=18$ in. for Steps 1-3. Then $Q=4.7$ mgd and $u=4.1$ ft/s for Step 4. From the hydraulic elements chart, $v_p=1.9$ ft/s, which is close enough. Thus the upstream invert elevation of Manhole 3 is

$$59.9 - (0.005)(200)=58.9\text{ ft},$$

And the downstream is at 58.8 ft, still well above the rock. From Manhole 3 to Manhole 4, the street obviously has too much slope. Try using $D=12$ in. and

$$s=(58.8 - 40)/100=0.188,$$

Since 40 ft is the desired invert elevation of Manhole 4. Read $Q=8.5$ mgd and $v=19$ ft/s, but only 3.2 mgd is required at maximum flow; hence

$$q/Q=3.2/8.5=0.38, \text{ and}$$

$$v_p=(0.78)(18\text{ft}/\sim)=14.8\text{ft/s}.$$

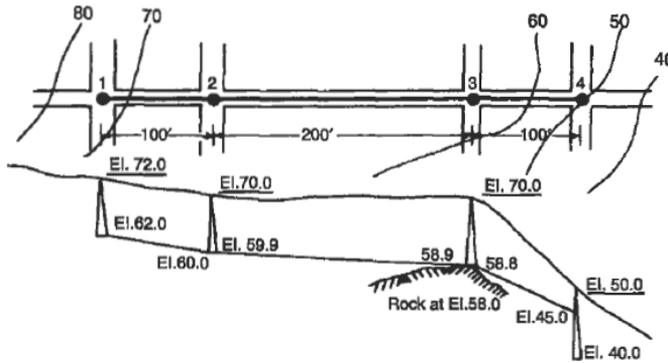
This is too high. Use a drop manhole, with the invert at, say, elevation 45.0. In this case $s=0.138$ and $Q=$

$$7.3\text{ mgd}, v=14.5\text{ s},$$

$$q/Q=3.2/7.3=0.44, \text{ and}$$

$$v_p=(0.85)(14.5\text{ ft/s})=12.3\text{ ft/s},$$

This is close enough. The upstream invert elevation of Manhole 4 is thus at 45.0 ft and the downstream invert elevation can be at, say, 40.0 ft. The minimum velocity for this last step need not be checked.



26. A community normally levies a sewer charge of 20 cents/in.³. For discharges in which the BOD > 250 mg/L and suspended solids (SS) > 300 mg/L, an additional \$0.50/kg BOD and \$1.00/kg SS are levied.

A chicken processing plant uses 2000 m³ water per day and discharges wastewater with BOD=480 mg/L and SS=1530 mg/L. What is the plant's daily wastewater disposal bill?

The excess BOD and SS are, respectively,

$$(480 - 250) \text{ mg/L} \times 2000 \text{ in.}^3 \times 1000 \text{ L/m}^3 \times 10^{-6} \text{ kg/mg} = 460 \text{ kg excess BOD}$$

$$(1530 - 300) \text{ mg/L} \times 2000 \text{ m}^3 \times 1000 \text{ L/m}^3 \times 10^{-6} \text{ kg/mg} = 2460 \text{ kg excess SS.}$$

The daily bill is thus

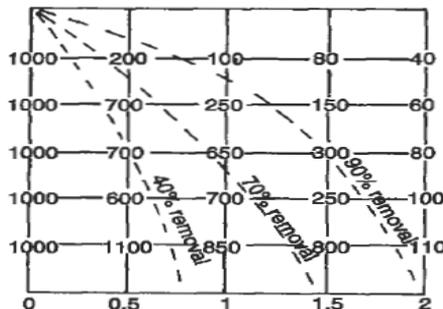
$$(2000 \text{ m}^3) (\$0.20/\text{m}^3) + (460 \text{ kg}_{\text{BOD}}) (\$0.50/\text{kg}_{\text{BOD}}) + (2460 \text{ kg}_{\text{SS}}) (\$1.00/\text{kg}_{\text{SS}}) = \$3090.00.$$

27. A primary clarifier has an overflow rate of 600 gal/day-ft² and a depth of 6 ft. What is its hydraulic retention time?

$$v_0 = 600 \frac{\text{gal}}{\text{day} - \text{ft}^2} \times \frac{1 \text{ ft}^3}{7.48 \text{ gal}} = 80.2 \text{ ft / day}$$

$$\bar{t} = \frac{H}{v_0} = \frac{6 \text{ ft}}{80.2 \text{ ft / day}} = 0.0748 \text{ day} = 1.8 \text{ h}$$

28. A chemical waste at an initial SS concentration of 1000 mg/L and flow rate of 200 m³/h is to be settled in a tank, H=1.2 m deep, W=10 m wide, and L=31.4 m long. The results of a laboratory test are shown in the figure. Calculate the fraction of solids removed the overflow rate, and the velocity of the critical particle.



The surface area of the tank is

$$A=WL=(31.4)(10)=314\text{m}^2$$

The overflow rate is therefore

$$Q/A=200/314=0.614\text{m}^3/\text{h}\cdot\text{m}^2$$

The critical velocity is thus $v_0=0.614\text{m}^3/\text{h}\cdot\text{m}^2$. However, the waste in this instance undergoes flocculent settling rather than settling at the critical velocity. The hydraulic retention time is

$$t = \frac{V}{Q} = \frac{AH}{Q} = \frac{(314)(1.2)}{200} = 1.88 \text{ h}$$

In the figure the 85% removal line approximately intersects the retention time of 1.88 h. Thus, 85% of the solids are removed. In addition to this, however, even better removal is indicated at the top of the water column. At the top 20cm, assume the SS concentration is 40mg/L, equal to $((1000 - 4) \times 100)/1000=96\%$ removal, or 11% better than the entire column. The second shows $((1000 - 60) \times 100)/1000=94\%$ removal and so on. The total amount removed, ignoring the bottommost section, is

$$R = P + \sum_{i=1}^{n-1} \left(\frac{h}{H} \right) (P_i - P) = 85 + (1/6)(11 + 9 + 5 + 4) = 90.9\%$$

29. The BOD₅ of the liquid from the primary clarifier is 120 mg/L at a flow rate of 0.05mgd. The dimensions of the aeration tank are 20 × 10 × 20 ft³ and the MLSS=2000 mg/L. Calculate the F/M ratio:

$$\frac{\text{lb BOD}}{\text{day}} = \left(\frac{120 \text{ mg}}{\text{L}} \right) (0.05 \text{ mgd}) \left(\frac{3.8 \text{ L}}{\text{gal}} \right) \left(\frac{1 \text{ lb}}{454 \text{ g}} \right) \left(\frac{1 \text{ g}}{1000 \text{ mg}} \right) = \left(\frac{50 \text{ lb}}{\text{day}} \right)$$

$$\text{lb MLSS} = (20 \times 10 \times 20) \text{ ft}^3 \left(\frac{2000 \text{ mg}}{\text{L}} \right) \left(\frac{3.8 \text{ L}}{\text{gal}} \right) \left(\frac{7.48 \text{ gal}}{\text{ft}^3} \right) \left(\frac{1 \text{ lb}}{454 \text{ g}} \right) \left(\frac{1 \text{ g}}{1000 \text{ mg}} \right) = 229 \text{ lb}$$

$$\frac{F}{M} = \frac{50}{229} = 0.22 \frac{\text{lb BOD} / \text{day}}{\text{lb MLSS}}$$

30. A sample of sludge has an SS concentration of 4000 mg/L. After settling for 30 min in a 1-L cylinder, the sludge occupies 400 mL. Calculate the SVI.

$$SVI = \frac{(1000)(400 \text{ mL})}{4000 \text{ mg} / \text{L}} = 100$$

31. An activated sludge system operates at a flow rate (Q) of 4000m³/day, with an incoming BOD (S₀) of 300 mg/L. A pilot plant showed the kinetic constants to be Y=0.5 kg SS/kg BOD, K_s=200 mg/L, μ=2/day. We need to design a treatment system that will produce an effluent BOD of 30mg/L (90% removal). Determine (a) the volume of the aeration tank, (b) the MLSS, and (c) the sludge age. How much sludge will be wasted daily?

The MLSS concentration is usually limited by the ability to keep an aeration tank mixed and to transfer sufficient oxygen to the microorganisms. Assume in this case that X=4000 mg/L the hydraulic retention is then obtained by:

$$t = \frac{0.5(300 - 30)(200 + 30)}{2(30)(4000)} = 0.129 \text{ day} = 3.1 \text{ h}$$

The volume of the tank is then

$$V = \bar{t}Q = 4000(0.129) = 516 \text{ m}^3$$

The sludge age is

$$\Theta_c = \frac{(4000 \text{ mg / L})(0.129 \text{ day})}{(0.5 \text{ kg SS / kg BOD})(300 - 30) \text{ mg / L}} = 3.8 \text{ days}$$

$$\frac{1}{\Theta_c} = \frac{\text{kg sludge wasted / day}}{\text{kg sludge in aeration tank}}$$

$$X_r Q_w = \frac{XV}{\Theta_c} = \frac{(4000)(516)(10^3 \text{ L / m}^3)(1/10^6 \text{ kg / mg})}{3.8} = 543 \text{ kg / day}$$

32. Raw primary and waste activated sludge containing 4% solids is to be anaerobically digested at a loading of 3 kg/m³ × day. The total sludge produced in the plant is 1500 kg of dry solids per day. Calculate the required volume of the primary digester and the hydraulic retention time.

The production of sludge requires

$$\frac{1500 \text{ kg / day}}{3 \text{ kg / m}^3 \text{ - day}} = 500 \text{ m}^3 \text{ digester volume}$$

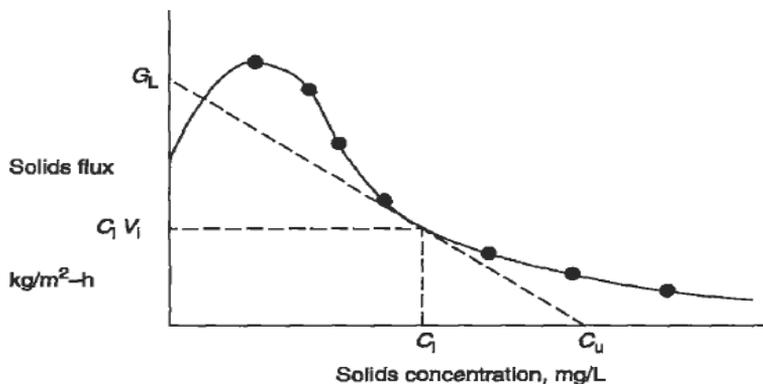
The total mass of wet sludge pumped to the digester is

$$\frac{1500 \text{ kg / day}}{0.04} = 37,500 \text{ kg / day}$$

Since 1 L of sludge weighs about 1 kg, the volume of sludge is 37,500 L/day or 37.5 m³/day, and the hydraulic residence time is

$$t = (500 \text{ m}^3) / (37.5 \text{ m}^3 / \text{day}) = 13.3 \text{ days.}$$

33. What would be the required area for a thickener if in the figure C_u was 25,000 mg/L, G_L was 3 kg/m²-h, and the feed was 60 m³/h of sludge with 1% solids?



$$A_L = \frac{Q_0 C_0}{G_L} = \frac{(60 \text{ m}^3 / \text{h})(0.01)(1000 \text{ kg / m}^3)}{3 \text{ kg / m}^2 \text{ - h}} = 200 \text{ m}^2$$

34. A sludge has a solids concentration of 4% and a specific resistance to filtration of 1.86×10^{13} m/kg. The pressure in a belt filter is expected to be 800 N/m² and the filtration time is 30 s. Estimate the belt area required for a sludge flow rate of 0.3 m³/s.

$$Y_F = \left[\frac{2(800)(40)}{(0.01)(1.86 \times 10^{13})(30)} \right]^{1/2} = 1.07 \times 10^{-4} \text{ kg} / \text{m}^2 \cdot \text{s}$$

This filter yield is approximately 8 lb/ft²-h, which is excellent production for a dewatering operation.

35. Assuming $W_i=400$ and x_c of the product is 1.62 cm, $n=1$, and $L_f=25$ cm (about 10 in.; a realistic estimate for raw refuse), find the expected power requirements for a shredder processing 10 tons/h.

$$W_i = \frac{10(400)}{\sqrt{16200 \times 1.61}} = 16.7 \text{ kWh} / \text{ton}$$

(Note: and L_f must be in μm)

The power requirement is (16.7 kWh/ton) (10 tons/h)=167 kW.

36. A binary separator, a magnet, is to separate a product, ferrous materials, from a feed stream of shredded refuse. The feed rate to the magnet is 1000 kg/h, and contains 50 kg of ferrous materials. The product stream weighs 40 kg, of which 35 kg are ferrous materials. What is the percent recovery of ferrous materials, their purity, and the overall efficiency?

$$x_0 = 50 \text{ kg}$$

$$y_0 = 1000 - 50 = 950 \text{ kg}$$

$$x_1 = 35 \text{ kg}$$

$$y_1 = 40 - 35 = 5 \text{ kg}$$

$$x_2 = 50 - 35 = 15 \text{ kg}$$

$$y_1 = 950 - 5 = 945 \text{ kg}$$

$$R_{(x_1)} = \left(\frac{35}{50} \right) 100 = 70\%$$

$$P_{(x_1)} = \left(\frac{35}{35 + 5} \right) 100 = 88\%$$

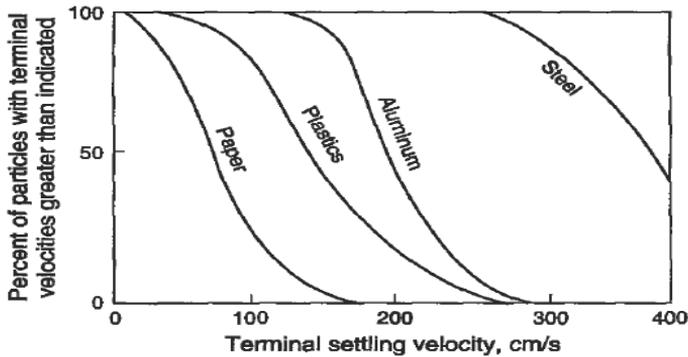
Then

$$E_{(x,y)} = \left(\frac{35}{50} \right) \left(\frac{945}{950} \right) 100 = 70\%$$

37. Find the critical speed for a 3-m-diameter trammel.

$$\eta_c = \sqrt{\frac{980}{4\pi^2 \times 150}} = 0.407 \text{ rotations} / \text{s}$$

38. An air classifier operates with an air velocity of 200 cm/s, and the feed contains equal amounts (by weight) of paper, plastics, aluminum, and steel, having terminal settling curves as shown in the figure. What would be the recovery of organic material, and what would be the purity of the recovered product?



Since each component is 25% by weight of the feed, $x_o = 25\% + 25\% = 50\%$ and $y_o = 25\% + 25\% = 50\%$.

From the figure, at 200 cm/s air velocity, the fractions of the components in the overflow (product) are:

Paper 100%

Plastics 80%

Aluminum 50%

Steel 0%

Thus the total percentage of organic materials in the product is

$$100 \times \frac{1}{4} + 80 \times \frac{1}{4} = 45\%$$

39. If carbon is combusted as

$C + O_2 \rightarrow CO_2 + \text{heat}$, how much air is required per gram of carbon?

One mole of oxygen is required for each mole of carbon used. The atomic weight of carbon is 12 g/g-atom and the molecular weight of O_2 is $2 \times 16 = 32$ g/mole. Hence 1 g of C requires $32/12 = 2.67$ g O_2

Air is 23.15% O_2 by weight; total amount of air required to combust 1 g of C is

$$2.67/0.2315 = 11.53 \text{ g air}$$

40. A processed refuse containing 20% moisture and 60% organic material is fed to a boiler at a rate of 1000 kg/h. From a calorimetric analysis of the refuse, a dry sample was determined to have a heat value of 19,000 kJ/kg. Calculate the thermal balance for this system.

The heat from combustion of the RDF is

$$H_{\text{comb}} = (19,000 \text{ kJ/kg}) (1000 \text{ kg/h}) = 19 \times 10^6 \text{ kJ/h.}$$

The organic fraction of the RDF contains hydrogen, which is combusted to water. Therefore, the heat of combustion value includes the latent heat of vaporization of water, because the water formed is vaporized during the combustion. Since this heat is absorbed by the water formed, it is a heat loss. Assuming that the organic constituents of the RDF are 50% hydrogen (by weight), and given that the latent heat of vaporization of water is 2,420 kJ/kg, the heat loss from the vaporization is

$$H_{\text{vsp}} = (1000 \text{ kg/h}) (0.6 \text{ organic}) (0.5 \text{ H}) (2420 \text{ kJ/kg}) = 0.726 \times 10^6 \text{ kJ/h.}$$

The RDF also contains moisture that is vaporized:

$$H_{\text{mois}} = (1000 \text{ kg/h}) (0.2 \text{ moisture}) (2420 \text{ kJ/kg}) = 0.484 \times 10^6 \text{ kJ/h.}$$

There is heat loss associated with radiation, usually assumed as 5% of the heat input. Not all of the organic materials will combust. Assume that the ashes contain 10% of the organic material, so that the heat loss is

$$H_{\text{rad}} = (19 \times 10^6 \text{ kJ/h}) (0.05) = 0.95 \times 10^6 \text{ kJ/h}$$

$$H_{\text{noncom}} = (10/60) (19 \times 10^6 \text{ kJ/h}) = 3.17 \times 10^7 \text{ kJ/h.}$$

The stack gases also contain heat, which is usually assumed to be the difference between the heat of combustion and the other losses calculated:

Heat input = Heat output

$$H_{\text{comb}} = H_{\text{vap}} + H_{\text{mois}} + H_{\text{rad}} + H_{\text{noncom}} + H_{\text{stack}}$$

$$19 \times 10^6 = (0.726 + 0.484 + 0.95 + 3.17) 10^6 + H_{\text{stack}}$$

$$H_{\text{stack}} = 13.67 \times 10^6 \text{ kJ/h.}$$

Some of the 13.67×10^6 KJ/h may be recovered by running cold water into the boiler through the water wall tubes and producing steam. If 2000 kg/h of steam at a temperature of 300°C and a pressure of 4000 kPa is required and the temperature of the boiler water is 80°C, calculate the heat loss in the stack gases.

Heat in the boiler water is

$$H_{\text{wat}} = (2000 \text{ kg/h}) (80 + 273) \text{ K} (0.00418) \text{ kJ/kg-K} = 2951 \text{ kJ/h.}$$

Where 0.00418 kJ/kg-K is the specific heat of water. The heat in the steam, at 300°C and 4000 kPa, is 2975 kJ/kg, so that

$$H_{\text{steam}} = (2000 \text{ kg/h}) (2975) \text{ kJ/kg} = 5.95 \times 10^6 \text{ kJ/h.}$$

The heat balance then yields

$$H_{\text{comb}} + H_{\text{wat}} = H_{\text{vap}} + H_{\text{mois}} + H_{\text{rad}} + H_{\text{noncom}} + H_{\text{steam}} + H_{\text{stack}}$$

$$(19 + 0.0002) 10^6 = (0.726 + 0.484 + 0.95 + 3.17 + 5.95) 10^6 + H_{\text{stack}}$$

$$H_{\text{stack}} = 7.72 \times 10^6 \text{ kJ/h}$$

41. An amount of 10.0 g of pure ^{60}Co is prepared. The equation for this nuclear reaction is $^{60}\text{Co} + ^1_0\text{n} \rightarrow ^{60}\text{Ni} + ^1_0\text{n}$.

The half-life of C-11 is 21 min. How many grams of C-11 will be left 24 h after the preparation? (Note that one atomic mass unit (amu) = 1.66×10^{-24} g.)

$$1 \text{ g} = \left(\frac{1}{11} \text{ mole} \right) (6.02 \times 10^{23} \text{ atoms / mole}) = 5.47 \times 10^{22} \text{ atoms} = N_0$$

$$24 \text{ h} = 24 \times 60 = 1440 \text{ min} = t$$

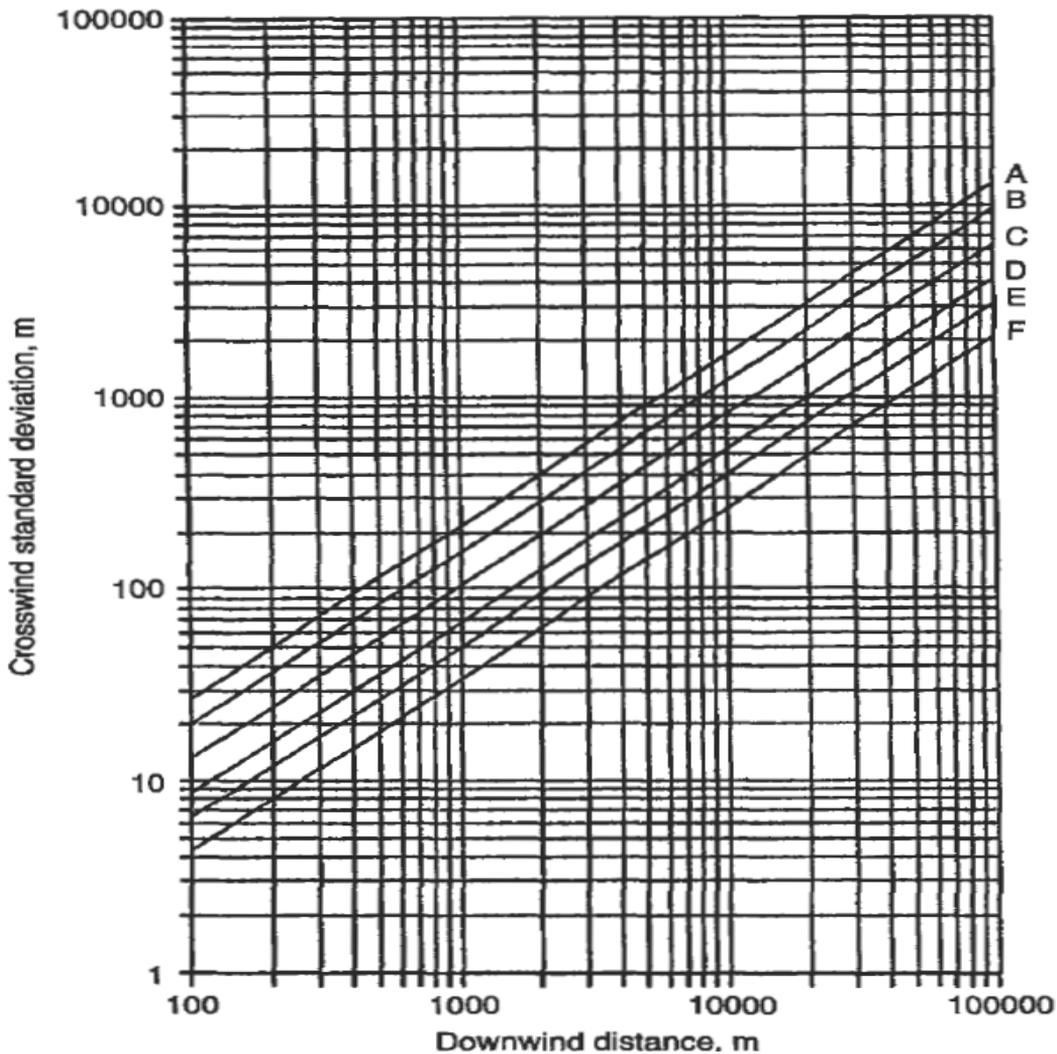
$$K_b = \ln 2 / t_{0.5} = 0.693 / 21 = 0.033 \text{ min}^{-1}$$

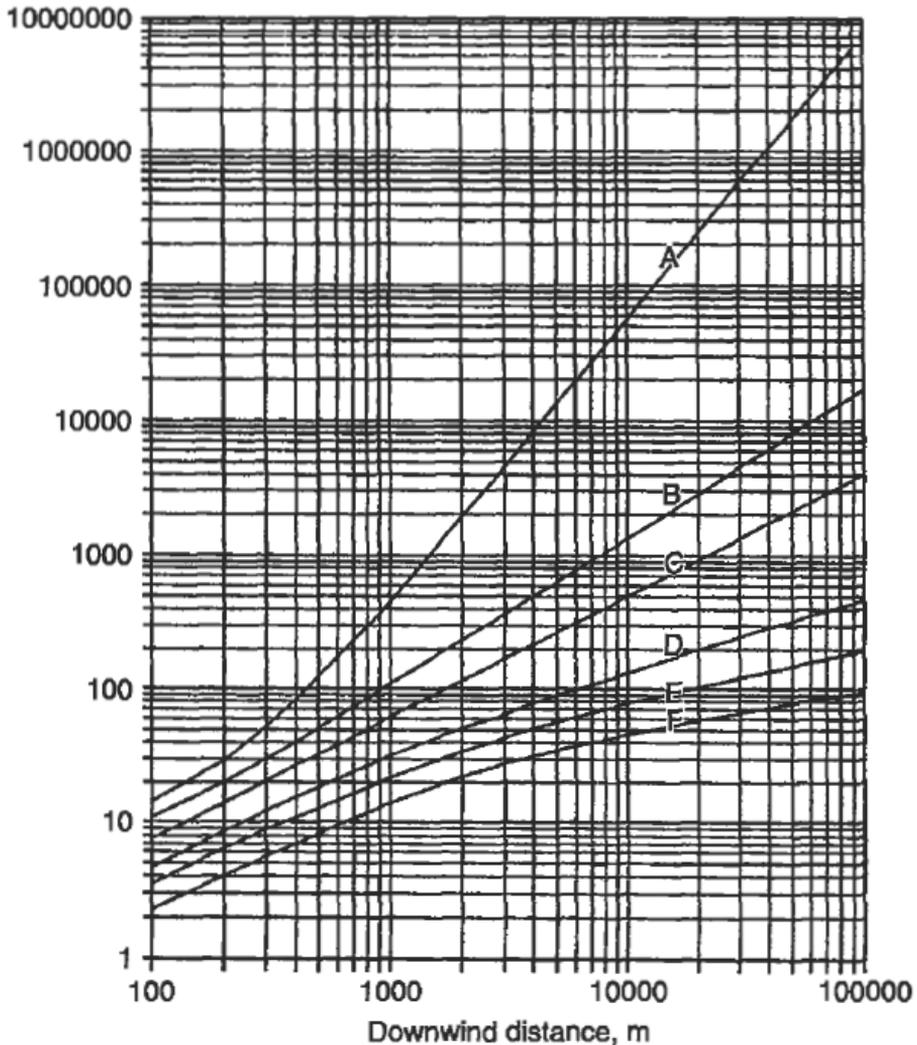
$$N = 5.47 \times 10^{22} \times e^{-47.52} = 126 \text{ atoms}$$

$$\frac{(116 \text{ atoms})(12 \text{ g / mole})}{6.02 \times 10^{23} \text{ atoms / mole}} = 2.52 \times 10^{-21} \text{ g}$$

42. An oil pipeline leak results in emission of 100g/h of H₂S. On a very sunny summer day, with a wind speed of 3.0m/s, what will be the concentration of H₂S 1.5 km directly downwind from the leak (Use the table and the figures)?

Wind speed at 10 m (m/s)	Day Incoming solar radiation			Night Thin overcast	
	Strong	Moderate	Slight	½ low cloud	3/8 cloud
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	E
>6	C	D	D	D	D





From the table, we may assume Class B stability. Then, from the figures, at $x=1.5$ km, σ_y is approximately 210 m and, σ_z is approximately 160m, and

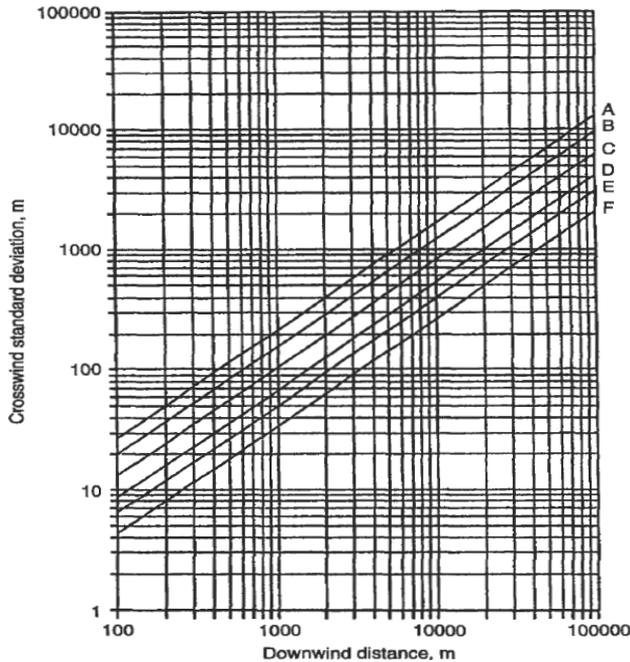
$$Q=100\text{g/h}=0.0278 \text{ g/s.}$$

$$C(1500,0,0) = \frac{0.0278 \text{ g/s}}{\pi(3.0 \text{ m/s})(210 \text{ m})(160 \text{ m})} = 0.088 \mu\text{g/m}^3$$

43. A coal-burning electric generating plant emits 1.1 kg/min of SO₂ from a stack with an effective height of 60m. On a thinly overcast evening, with a wind speed of 5.0 m/s, what will be the ground level concentration of SO₂ 500 m directly downwind from the stack (Use the table and the figure.)?

Wind Speed at 10 m (m/s)	Day Incoming solar radiation			Night Thin overcast	
	Strong	Moderate	Slight	½ low cloud	3/8 cloud
<2	A	A-B	B		

2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	E
>6	C	D	D	D	D



From the table, we may assume Class D stability. Then, from the figure, at $x=0.5$ km, σ_y is approximately 35 m and σ_z is approximately 19 m, and

$$Q=1.1\text{kg}/\text{min}=18\text{g}/\text{s}.$$

In this problem, the release is elevated, and $H=60$ m.

$$C(0.5,0,0)=\frac{18\text{ g/s}}{\pi(5\text{ m/s})(35\text{ m})(19\text{ m})}\exp\left(\frac{-(60)^2}{2(19)^2}\right)=11.8\text{ }\mu\text{g}/\text{m}^3$$

44. A power plant has a stack with a diameter of 2 m and emits gases with a stack exit velocity of 15 m/s and a heat emission rate of 4,800 Kj/s. The wind speed is 5 m/s. Stability is neutral. Estimate the plume rise. If the stack has a geometric height of 40 m, what is the effective stack height?

$$\Delta h = 0.35 \frac{15 \times 2}{5} + 2.64 \frac{\sqrt{4800}}{5} = 38.7\text{ m}$$

$$H = h_g + h = 40 + 38.7 = 78.7\text{ m}$$

45. A clean filter is found to weigh 10.00g. After 24 h in a hi-vol sampler, the filter plus dust weighs 10.10g. The air flow at start and end of the test was 60 and 40 ft³/min, respectively. What is the concentration of particulate matter?

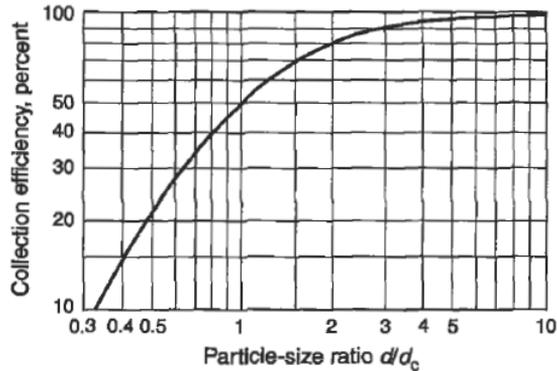
$$\text{Weight of the particulates (dust)}=(10.10 - 10.00)\text{ g} \times 10^6\text{ }\mu\text{g}/\text{g}=0.1 \times 10^6\text{ }\mu\text{g}.$$

$$\text{Average air flow}=(60+40)/2=50\text{ ft}^3/\text{min}.$$

Total air through the filter = $50 \text{ ft}^3/\text{min} \times 60 \text{ min/h} \times 24 \text{ h/day} \times 1 \text{ day} = 2038 \text{ m}^3$.

Total suspended particulate matter = $(0.1 \times 10^6 \text{ } \mu\text{g}) / 2038 \text{ m}^3 = 49 \text{ } \mu\text{g}/\text{m}^3$.

46. A cyclone has an inlet width of 10 cm and four effective turns ($N=4$). The gas temperature is 350 K and the inlet velocity is 10 m/s. The average particle diameter is 8 μm and the average density is 1.5 g/cm^3 . What is the collection efficiency (Use the figure)?



The viscosity of air at 350 K is 0.0748 kg/m-h. We can assume that ρ is negligible compared to ρ_s :

$$d_c = \sqrt{\frac{9 \times 0.0748 \text{ kg/m-h} \times 0.1 \text{ m}}{2\pi \times 4 \times 10 \times 3600 \times 1500}} = 7.04 \text{ } \mu\text{m}$$

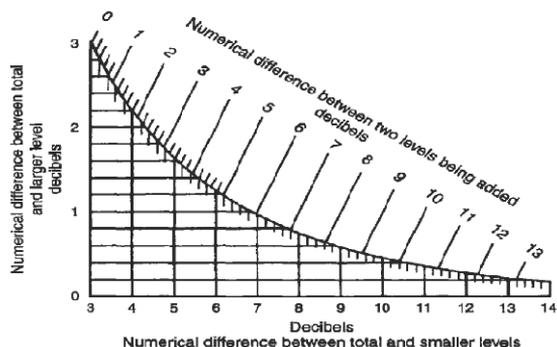
$$\frac{d}{d_c} = \frac{8}{7.04} = 1.14$$

and from the figure, the expected removal efficiency is about 55%.

47. In cast iron, sound waves travel at about 3440 m/s. What would be the wavelength of a sound from a train if it rumbles at 50 cycles/s and one listens to it placing an ear on the track?

$$\lambda = \frac{c}{v} = \frac{3440}{50} = 69 \text{ m}$$

48. A jet engine has a sound intensity level of 80dB, as heard from a distance of 50 ft. A ground crew member is standing 50 ft from a four-engine jet. What SPL reaches her ear when the first engine is turned on? The second, so that two engines are running? The third? Then all four (Use the figure.)?



When the first engine is turned on, the SPL is 80 dB, provided there is no other comparable noise in the vicinity. To determine, from the chart, what the SPL is when the second engine is turned on, we note that the difference between the two engine intensity levels is

$$80 - 80 = 0.$$

From the chart, a numerical difference of 0 between the two levels being added gives a difference of 3 between the total and the larger of the two. The total SPL is thus

$$80 + 3 = 83 \text{ dB},$$

When the third engine is turned on, the difference between the two levels is

$$83 - 80 = 3 \text{ dB},$$

Yielding a difference from the total of 1.8, for a total IL of

$$83 + 1.8 = 84.8 \text{ dB},$$

When all four engines are turned on, the difference between the sounds is

$$84.8 - 80 = 4.8 \text{ dB},$$

yielding a difference from the total of 1.2, for a total IL of 86 dB.

49. Calculate the settling velocity of a particle moving in a gas stream.

Assume the following Information Given:

d_p = particle diameter = 45 μm (45 microns)

g = gravity forces = 980 cm/sec^2

ρ_p = particle density = 0.899 g/cm^3

ρ_a = fluid (gas) density = 0.012 g/cm^3

μ = fluid (gas) viscosity = $1.82 \times 10^{-4} \text{g}/\text{cm}\cdot\text{sec}$

C_f = 1.0 (if applicable)

Step 1. Calculate the K parameter to determine the proper flow regime:

$$K = d_p (g \rho_p \rho_a / \mu^2)^{0.33} = 45 \times 10^{-4} (980 \times 0.899 \times 0.012 / (1.82 \times 10^{-4})^2)^{0.33} = 3.07$$

The result demonstrates that the flow regime is laminar.

Step 2. Determine the settling velocity:

$$v = g \rho_p d_p^2 C_f / 18 \mu = 980 \times 0.899 \times (45 \times 10^{-4})^2 \times 1 / (18 \times 1.82 \times 10^{-4}) = 5.38 \text{ cm}/\text{sec}$$

50. Three differently sized fly ash particles settle through the air. Calculate the particle terminal velocity (assume the particles are spherical) and determine how far each will fall in 30 sec.

Given:

Fly ash particle diameters = 0.4, 40, 400 μm

Air temperature and pressure = 238°F, 1 atm

Specific gravity of fly ash = 2.31

Because the Cunningham correction factor is usually applied to particles equal to or smaller than 1 μm , check how it affects the terminal settling velocity for the 0.4 μm particle.

Step 1. Determine the value for K for each fly ash particle size settling in air. Calculate the

particle density using the specific gravity given:

$$P_p = \text{particle density} = \text{specific gravity of fly ash} \times \text{density of water} = 2.31 \times 62.4 = 144.14 \text{ lb/ft}^3$$

Calculate the density of air:

$$p = \text{air density} = PM/RT = 1 \times 29 / (0.7302 \times (238 + 460)) = 0.0569 \text{ lb/ft}^3$$

$$\mu = \text{air viscosity} = 0.021 \text{ cp} = 1.41 \times 10^{-5} \text{ lb/ft} \cdot \text{sec}$$

Determine the flow regime (K):

$$K = d_p (g p_p p_a / \mu^2)^{0.33}$$

$$\text{For } d_p = 0.4 \mu\text{m:}$$

$$K = ((0.4) / (25400) (12)) (32.2 (144.14) (0.0569) / (1.41 \times 10^{-5})^2)^{0.33} = 0.0144$$

$$\text{For } d_p = 40 \mu\text{m:}$$

$$K = ((40) / (25400) (12)) (32.2 (144.14) (0.0569) / (1.41 \times 10^{-5})^2)^{0.33} = 1.44$$

$$\text{For } d_p = 400 \mu\text{m:}$$

$$K = ((400) / (25400) (12)) (32.2 (144.14) (0.0569) / (1.41 \times 10^{-5})^2)^{0.33} = 14.4$$

Select the appropriate law, determined by the numerical value of K:

$K < 3.3$; Stokes' law range

$3.3 < K < 43.6$; intermediate law range

$43.6 < K < 2360$; Newton's law range

For $d_p = 0.4 \mu\text{m}$, the flow regime is laminar

For $d_p = 40 \mu\text{m}$, the flow regime is also laminar

For $d_p = 400 \mu\text{m}$, the flow regime is the transition regime

For $d_p = 0.4 \mu\text{m}$:

$$v = g p_p d_p^2 / 18 \mu = 32.2 \times ((0.4) / (25400 \times 12))^2 \times 144.14 / (18 \times 1.41 \times 10^{-5}) = 3.15 \times 10^{-5} \text{ ft/sec}$$

For $d_p = 40 \mu\text{m}$:

$$v = g p_p d_p^2 / 18 \mu = 32.2 \times ((40) / (25400 \times 12))^2 \times 144.14 / (18 \times 1.41 \times 10^{-5}) = 0.315 \text{ ft/sec}$$

For $d_p = 400 \mu\text{m}$ (use transition regime equation):

$$v = 0.153 g^{0.71} d_d^{1.14} p_p^{0.71} (\mu^{0.43} p^{0.29})$$

$$= 0.153 \times 32.2^{0.71} \times ((400) / (25400 \times 12))^{1.14} (144.14)^{0.71} / ((1.41 \times 10^{-5})^{0.43} (0.0569)^{0.29}) = 8.90 \text{ ft/sec}$$

Step4. Calculate distance.

For $d_p = 40 \mu\text{m}$, distance = time \times velocity:

$$\text{Distance} = 30 \times 0.315 = 9.45 \text{ ft}$$

For $d_p = 400 \mu\text{m}$, distance = time \times velocity:

$$\text{Distance} = 30 \times 8.90 = 267 \text{ ft}$$

For $d_p = 0.4 \mu\text{m}$, without Cunningham correction factor, distance = time \times velocity:

$$\text{Distance} = 30 \times 3.15 \times 10^{-5} = 94.5 \times 10^{-5} \text{ ft}$$

For $d_p = 0.4 \mu\text{m}$ with Cunningham correction factor, the velocity term must be corrected. For our purposes, assume particle diameter = $0.5 \mu\text{m}$ and temperature = 212°F to find the C_c

value. Thus, C_f is approximately equal to 1.446.

$$\text{The corrected velocity} = vC_f = 3.15 \times 10^{-5} \times 10^{-5} \times 1.446 = 4.55 \times 10^{-5}$$

$$\text{Distance} = 30 \times 4.55 \times 10^{-5} = 1.365 \times 10^{-3} \text{ ft}$$

51. Determine the minimum distance downstream from a cement dust-emitting source that will be free of cement deposit. The source is equipped with a cyclone.

Given:

Particle size range of cement dust=2.5 to 50.0 μm

Specific gravity of the cement dust=1.96

Wind speed=3.0 mi/h

The cyclone is located 150 ft above ground level. Assume ambient conditions are At 60°F and 1 atm. Disregard meteorological aspects.

Step 1: A particle diameter of 2.5 μm is used to calculate the minimum distance downstream free of dust because the smallest particle will travel the greatest horizontal distance.

Step 2: Determine the value of K for the appropriate size of the dust. Calculate the particle density (p_p) using the specific gravity given:

$$p_p = (\text{specific gravity of fly ash}) (\text{density of water}) = 1.96 \times 62.4 = 122.3 \text{ lb/ft}^3$$

Calculate the air density (p). Use modified ideal gas equation, $PV = nR_u T = (m/M)R_u T$

$$P = \text{mass} \times \text{volume} = PM/R_u T = (1) (29) / (0.73(60+460)) = 0.0764 \text{ lb/ft}^3$$

Determine the flow regime (K):

$$K = d_p (gp_p p_a / \mu^2)^{0.33}$$

For $d_p = 2.5 \mu\text{m}$:

$$K = ((2.5)/(25400) (12)) (32.2(122.3) (0.0764)/(1.22 \times 10^{-5})^2)^{0.33} = 0.104$$

Step 3: Determine which fluid-particle dynamic law applies for the preceding value of K. Compare the K value of 0.104 with the following range:

$K < 3.3$; Stokes' law range

$3.3 \leq K < 43.6$; intermediate law range

$43.6 < K < 2360$; Newton's law range

The flow is in the Stokes' law range; thus it is laminar.

Step 4: Calculate the terminal settling velocity in feet per second. For Stokes' law range, the velocity is

$$v = gp_p d_p^2 / 18\mu = 32.2 \times ((2.5)/(25400 \times 12))^2 \times 122.3 / (18 \times 1.22 \times 10^{-5}) = 1.21 \times 10^{-3} \text{ ft/sec}$$

Step 5: Calculate the time for settling:

$$t = (\text{outlet height}) / (\text{terminal velocity}) = 150 / 1.21 \times 10^{-3} = 1.24 \times 10^5 \text{ sec} = 34.4 \text{ h}$$

Step 6. Calculate the horizontal distance traveled:

$$\text{Distance} = \text{time for descent} \times \text{wind speed} = (1.24 \times 10^5) (3.0/3600) = 103.3 \text{ miles}$$

52. A hydrochloric acid mist in air at 25°C is collected in a gravity settler. Calculate the smallest mist droplet (spherical in shape) collected by the settler. Stokes' law applies; assume the acid concentration is uniform through the inlet cross-section of the unit.

Given:

Dimensions of gravity settler=30 ft wide, 20 ft high, 50 ft long

Actual volumetric flow rate of acid gas in air=50 ft³/sec

Specific gravity of acid=1.6

Viscosity of air=0.0185 cp=1.243 × 10⁻⁵ lb/ft-sec

Density of air=0.076 lb/ft³

Step 1: Calculate the density of the acid mist using the specific gravity given:

$$p_p = \text{particle density} = (\text{specific gravity of fly ash}) (\text{density of water}) = 1.6 \times 62.4 = 99.84 \text{ lb/ft}^3$$

Step 2: Calculate the minimum particle diameter in feet and microns, assuming that Stokes' law applies.

For Stokes' law range:

$$\text{Minimum } d_p = \sqrt{18\mu Q / g p_p B L} = \sqrt{18 \times 1.243 \times 10^{-5} \times 50 / (32.2 \times 99.84 \times 30 \times 50)} = 14.7 \mu\text{m}$$

53. A settling chamber that uses a traveling grate stoker is installed in a small heat plant. Determine the overall collection efficiency of the settling chamber, given the operating conditions, chamber dimensions, and particle size distribution data.

Given:

Chamber width=10.8 ft

Chamber height=2.46 ft

Chamber length=15.0 ft

Volumetric flow rate of contaminated air stream=70.6 scfs

Flue gas temperature=446°F

Flue gas pressure=1 atm

Particle concentration=0.23 gr/scf

Particle specific gravity=2.65

Standard conditions=32°F, 1 atm

Particle size distribution data of the inlet dust from the traveling grate stoker are shown in the table. Assume that the actual terminal settling velocity is one-half of the Stokes' law velocity.

Particle size range, μm	Average particle diameter μm	Inlet	
		Grains/scf	Wt%
0-20	10	0.0062	2.7
20-30	25	0.0159	6.9
30-40	35	0.0216	9.4
40-50	45	0.0242	10.5
50-60	55	0.0242	10.5
60-70	65	0.0218	9.5
70-80	75	0.0161	7
80-94	85	0.0218	9.5
94	94	0.0782	34
Total		0.23	100

Step 1: Plot the size efficiency curve for the settling chamber. The size efficiency curve is needed to calculate the outlet concentration for each particle size (range). These outlet concentrations are then used to calculate the overall collection efficiency of the settling chamber. The collection efficiency for a settling chamber can be expressed in terms of the terminal velocity, volumetric flow rate of contaminated stream, and chamber dimensions:

$$\eta = vBL/Q = (gp_p d_p^2 / 18\mu) (BL/Q)$$

Step 2: Express the collection efficiency in terms of the particle diameter d_p . Replace the terminal settling velocity in the preceding equation with Stokes' law. Because the actual terminal settling velocity is assumed to be one half of the Stokes' law velocity (according to the given problem statement), the velocity equation becomes:

$$v = gd_p^2 p_p / 36 \mu$$

$$\eta = (gp_p d_p^2 / 36 \mu) (BL/Q)$$

Determine the viscosity of the air in pounds per foot-second:

$$\text{Viscosity of air at } 446^\circ\text{F} = 1.75 \times 10^{-5} \text{ lb/ft-sec}$$

Determine the particle density in pounds per cubic foot:

$$P_p = 2.65(62.4) = 165.4 \text{ lb/ft}^3$$

Determine the actual flow rate in actual cubic feet per second. To calculate the collection efficiency of the system at the operating conditions, the standard volumetric flow rate of contaminated air of 70.6 scfs is converted to actual volumetric flow of 130 acfs:

$$Q_a = Q_s (T_a/T_s) = 70.6 (446+460)/(32=460) = 130 \text{ acfs}$$

Express the collection efficiency in terms of d_p , with d_p in feet. Also express the collection efficiency in terms of d_p , with d_p in microns.

Use the following equation; substitute values for p_p , g , B , L , μ , and Q in consistent units. Use the conversion factor for feet to microns. To convert d_p from square feet to square microns, d_p is divided by $(304,800)^2$.

$$\eta = (gp_p d_p^2 / 36 \mu) (BL/Q)$$

$$= (32.2) (165.4) (10.8) (15) (d_p)^2 / ((36) (1.75 \times 10^{-5}) (130) (304800)^2) = 1.134 \times 10^{-4} (d_p)^2$$

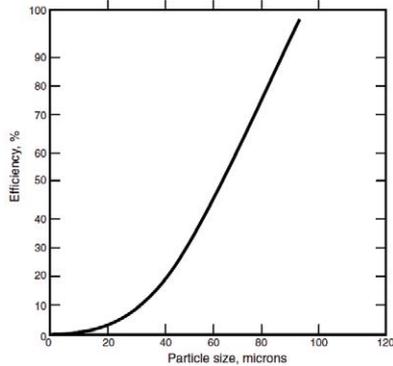
Where d_p is in microns.

Calculate the collection efficiency for each particle size. For a particle diameter of 10 μm :

$$\eta = (1.134 \times 10^{-4}) (d_p)^2 = (1.134 \times 10^{-4}) (10)^2 = 1.1\%$$

$d_p, \mu\text{m}$	$\eta, \%$
94	100
90	92
80	73
60	41
40	18.2
20	4.6
10	1.11

The size efficiency curve for the settling chamber is shown in the figure; read off the collection efficiency of each particle size from this figure.



Calculate the overall collection efficiency.

$d_p, \mu\text{m}$	Weight fraction, W_i	η_i
10	0.027	1.1
25	0.069	7.1
35	0.094	14
45	0.105	23
55	0.105	34
65	0.095	48
75	0.07	64
85	0.095	83
94	0.34	100
Total	1	

$$\eta_c = \sum W_i \eta_i = 0.027 \times 1.1 + 0.069 \times 7.1 + 0.094 \times 14.0 + 0.105 \times 23.0 + 0.105 \times 34.0 + 0.095 \times 48.0 + 0.07 \times 64.0 + 0.095 \times 83.0 + 0.34 \times 100 = 59.0\%$$

54. Determine the cut size diameter and overall collection efficiency of a cyclone, given the particle size distribution of a dust from a cement kiln.

Given:

Gas viscosity $\mu = 0.02$ centipoises (cP) $= 0.02(6.72 \times 10^{-4})$ lb/ft-sec

Specific gravity of the particle $= 2.9$

Inlet gas velocity to cyclone $= 50$ ft/sec

Effective number of turns within cyclone $= 5$

Cyclone diameter $= 10$ ft

Cyclone inlet width $= 2.5$ ft

Particle size distribution data are shown in the table.

Average particle size in range $d_p, \mu\text{m}$	% wt
1	3
5	20
10	15
20	20
30	16
40	10
50	6
60	3
>60	7

Step 1: Calculate the cut diameter $(d_p)_{\text{cut}}$, which is the particle collected at 50% efficiency.

For cyclones:

$$(d_p)_{cut} = \{9\mu B_c / (2\pi n_{ti} (p_p - p_g))\}^{0.5}$$

Determine the value of $p_p - p$. Because the particle density is much greater than the gas density, $p_p - p$ can be assumed to be p_p :

$$p_p - p = p_p = 2.9(62.4) = 180.96 \text{ lb/ft}^3$$

Calculate the cut diameter:

$$(d_p)_{cut} = ((9) (0.02) (6.72 \times 10^{-4}) (2.5) / (2\pi \times 5 \times 50 \times 180.96))^{0.5} = 9.94 \text{ } \mu\text{m}$$

Step 2: Complete the size efficiency table using Lapple's method.

$d_p, \mu\text{m}$	w_i	$d_p / (d_p)_{cut}$	$\eta, \%$	$w_i \eta_i$
1	0.03	0.1	0	0
5	0.2	0.5	20	4
10	0.15	1	50	7.5
20	0.2	2	80	16
30	0.16	3	90	14.4
40	0.1	4	93	9.3
50	0.06	5	95	5.7
60	0.03	6	98	2.94
>60	0.07	-	100	7

As mentioned, this method provides the collection efficiency as a function of the ratio of particle diameter to cut diameter. Use the equation

$$\eta = 1 - (1.0) / (1.0 + (d_p / (d_p)_{cut})^2)$$

Step 3: Determine overall collection efficiency:

$$\sum w_i \eta_i = 0 + 4 + 7.5 + 16 + 14.4 + 9.3 + 5.7 + 2.94 + 7 = 66.84\%$$

55. An air pollution control officer has been asked to evaluate a permit application to operate a cyclone as the only device on the ABC Stonework's plant's gravel drier.

Given (design and operating data from permit application):

Average particle diameter=7.5 μm

Total inlet loading to cyclone=0.5 gr/ft³ (grains per cubic foot)

Cyclone diameter=2.0 ft

Inlet velocity=50 ft/sec

Specific gravity of the particle=2.75

Number of turns=4.5 turns

Operating temperature=70°F

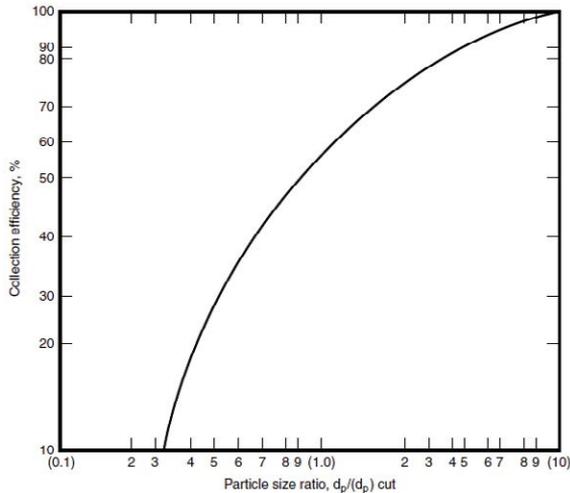
Viscosity of air at operating temperature=1.21 $\times 10^{-5}$ lb/ft-sec

The cyclone is a conventional one.

Air pollution control agency criteria:

Maximum total outlet loading=0.1 gr/ft³

Cyclone efficiency as a function of particle size ratio is provided in the figure (Lapple's curve).



Step 1: Determine the collection efficiency of the cyclone. Use Lapple’s method, which provides collection efficiency and values from a graph relating efficiency to the ratio of average particle diameter to the cut diameter. Again, the cut diameter is the particle diameter collected at 50% efficiency. Calculate the cut diameter using the Lapple method:

$$(d_p)_{cut} = \{9\mu B_c / (2\pi n_{tvi} (p_p - p_g))\}^{0.5}$$

Determine the inlet width of the cyclone, B_c . The permit application has established this cyclone as conventional. The inlet width of a conventional cyclone is one fourth of the cyclone diameter:

$$B_c = \text{cyclone diameter} / 4 = 2.0 / 4 = 0.5 \text{ ft}$$

Determine the value of $p_p - p$. Because the particle density is much greater than the gas density, $p_p - p$ can be assumed to be p_p :

$$p_p - p = p_p = 2.75(62.4) = 171.6 \text{ lb/ft}^3$$

Calculate the cut diameter:

$$(d_p)_{cut} = \{9\mu B_c / (2\pi n_{tvi} (p_p - p_g))\}^{0.5} = ((9) (1.21 \times 10^{-5}) (0.5) / (2\pi \times 4.5 \times 50 \times 171.6))^{0.5} = 4.57 \mu$$

Calculate the ratio of average particle diameter to the cut diameter:

$$d / (d_p)_{cut} = 7.5 / 4.57 = 1.64$$

Determine the collection efficiency utilizing Lapple’s curve

$$\eta = 72\%$$

Step 2: Calculate the required collection efficiency for the approval of the permit:

$$\mu = ((\text{inlet loading} - \text{outlet loading}) / (\text{inlet loading})) (100) = ((0.5 - 0.1) / 0.5) 100 = 80\%$$

Step 3: Should the permit be approved? Because the collection efficiency of the cyclone is lower than the collection efficiency required by the agency, the permit should not be approved.

56. A horizontal parallel-plate electrostatic precipitator consists of a single duct, 24 ft high and 20 ft deep, with an 11 in. plate-to-plate spacing. Given collection efficiency at a gas flow rate of 4200 actual cubic feet per minute (acfm), determine the bulk velocity of the gas, outlet loading, and drift velocity of this electrostatic precipitator. Also calculate revised collection efficiency if the flow rate and the plate spacing are changed.

Given:

Inlet loading=2.82 gr/ft³ (grains per cubic foot)

Collection efficiency at 4200 acfm=88.2%

Increased (new) flow rate=5400 acfm

New plate spacing=9 in.

Step 1: Calculate the bulk flow (throughout) velocity v . The equation for calculating throughput velocity is

$$V=Q/S=(4200)/((11/12) (24))=3.2 \text{ ft/sec}$$

Step 2: Calculate outlet loading. Remember that

$$\eta=(\text{fractional})=(\text{inlet loading} - \text{outlet loading})/(\text{inlet loading})$$

Therefore,

$$\text{Outlet loading}=(\text{inlet loading}) (1-\eta)=(2.82) (1 - 0.882)=0.333 \text{ gr/ft}^3$$

Step 3: Calculate the drift velocity, which is the velocity at which the particle migrates toward the collection electrode with the electrostatic precipitator.

$$\eta=1 \exp (-wA/Q)$$

Calculate the collection surface area A . Remember that the particles will be collected on both sides of the plate.

$$A=(2) (24) (20)=960 \text{ ft}^2$$

Calculate the drift velocity w . Because the collection efficiency, gas flow rate, and collection surface area are now known, the drift velocity can easily be found from the Deutsch-Anderson equation:

$$\eta=1 \exp (-wA/Q)$$

$$0.882=1 - \exp (-960) (w)/(4200))$$

Solving for w :

$$w=9.36 \text{ ft/min}$$

Step 4: Calculate the revised collection efficiency when the gas volumetric flow rate is increased to 5400 cfm. Assume the drift velocity remains the same:

$$\eta=1 \exp (-wA/Q)=1 - \exp (-960)(9.36)/(5400))=81.2\%$$

Step 5: Does the collection efficiency change with changed plate spacing? No. Note that the Deutsch-Anderson equation does not contain a plate-spacing term.

57. Calculate the collection efficiency of an electrostatic precipitator containing three ducts with plates of a given size, assuming a uniform distribution of particles. Also, determine the collection efficiency if one duct is fed 50% of the gas and the other passages are fed 25% each.

Given:

Volumetric flow rate of contaminated gas=4000 acfm

Operating temperature and pressure=200°C and 1 atm

Drift velocity=0.40 ft/sec

Size of the plate=12 ft long and 12 ft high

Plate-to-plate spacing=8 in.

Step 1: What is the collection efficiency of the electrostatic precipitator with a uniform volumetric flow rate to each duct? Use the Deutsch–Anderson equation to determine the collection efficiency of the electrostatic precipitator.

$$\eta = 1 - \exp(-wA/Q)$$

Calculate the collection efficiency of the electrostatic precipitator using the Deutsch–Anderson equation.

The volumetric flow rate (Q) through a passage is one third of the total volumetric flow rate:

$$Q = (4000)/(3) (60) = 22.22 \text{ acfs}$$

$$\eta = 1 - \exp(-wA/Q) = 1 - \exp(-(288) (0.4)/(22.22)) = 99.44\%$$

Step 2: What is the collection efficiency of the electrostatic precipitator, if one duct is fed 50% of gas and the others 25% each? The collection surface area per duct remains the same. What is the collection efficiency of the duct with 50% of gas, η_1 ? Calculate the volumetric flow rate of gas through the duct in actual cubic feet per second:

$$Q = (4000)/(2) (60) = 33.33 \text{ acfs}$$

Calculate the collection efficiency of the duct with 50% of gas:

$$\eta_1 = 1 - \exp(-(288) (0.4)/(33.33)) = 96.84\%$$

What is the collection efficiency (η_2) of the duct with 25% of gas flow in each? Calculate the volumetric flow rate of gas through the duct in actual cubic feet per second:

$$Q = (4000)/(4) (60) = 16.67 \text{ acfs}$$

Calculate the collection efficiency (η_2) of the duct with 25% of gas:

$$\eta_2 = 1 - \exp(-(288) (0.4)/(16.67)) = 99.90\%$$

Calculate the new overall collection efficiency. The equation becomes:

$$\eta_t = (0.5) (\eta_1) + (2) (0.25) (\eta_2) = (0.5) (96.84) + (2) (0.25) (99.90) = 98.37\%$$

58. A vendor has compiled fractional efficiency curves describing the performance of a specific model of an electrostatic precipitator. Although these curves are not available, the cut diameter is known. The vendor claims that this particular model will perform with a given efficiency under particular operating conditions. Verify this claim and make certain the effluent loading does not exceed the standard set by USEPA.

Given:

Plate-to-plate spacing=10 in.

Cut diameter=0.9 μm

Collection efficiency claimed by the vendor=98%

Inlet loading=14 gr/ft³

USEPA standard for the outlet loading=0.2 gr/ft³ (maximum)

The particle size distribution is given in the table.

Weight range	Average particlesize d_p , μm
0-20	3.5
20-40	8
40-60	13
60-80	19
80-100	45

A Deutsch–Anderson type of equation describing the collection efficiency of an electrostatic precipitator is:

$$\eta = 1 - \exp(-Kd_p)$$

Step 1: Is the overall efficiency of the electrostatic precipitator equal to or greater than 98%? Because the weight fractions are given, collection efficiencies of each particle size are needed to calculate the overall collection efficiency.

Determine the value of K by using the given cut diameter. Because the cut diameter is known, we can solve the Deutsch–Anderson type equation directly for K.

$$\eta = 1 - \exp(-Kd_p)$$

$$0.5 = 1 - \exp(-K(0.9))$$

$$\exp(-K(0.9)),$$

$$K = 0.77$$

Calculate the collection efficiency using the Deutsch–Anderson equation where $d_p = 3.5$:

$$\eta = 1 - \exp((-0.77)(3.5)) = 0.9325$$

Weight fraction W_i	Average particle size d_p , μm	η_i
0.2	3.5	0.9325
0.2	8	0.9979
0.2	13	0.9999
0.2	19	0.9999
0.2	45	0.9999

Calculate the overall collection efficiency.

$$\eta = \sum W_i \eta_i = 0.2 \times 0.9325 + 0.2 \times 0.9979 + 0.2 \times 0.9999 + 0.2 \times 0.9999 + 0.2 \times 0.9999 = 98.61\%$$

Is the overall collection efficiency greater than 98%? Yes

Step 2: Does the outlet loading meet USEPA’s standard? Calculate the outlet loading in grains per cubic foot:

$$\text{Outlet loading} = (1.0 - \eta) (\text{inlet loading})$$

Where η is the fractional efficiency for the preceding equation

$$\text{Outlet loading} = ((1.0 - 0.9861)(14)) = 0.195 \text{ gr/ft}^3$$

Is the outlet loading less than 0.2 gr/ft³? Yes.

Step 3: Is the vendor’s claim verified? Yes.

59. A proposal to install a pulse jet fabric filter system for cleaning an air stream containing particulate matter must be evaluated. Select the most appropriate filter bag, considering performance and cost.

Given:

Volumetric flow rate of polluted air stream = 10,000 scfm (60°F, 1 atm)

Operating temperature = 250°F

Concentration of pollutants = 4 gr/ft³

Average air-to-cloth ratio (A/C ratio) = 2.5 cfm/ft² cloth

Collection efficiency requirement = 99%

The table lists information given by filter bag manufacturers. Assume no bag has an

advantage from the standpoint of durability under the operating conditions for which the bag is to be designed.

Property	Filter bag A	Filter bag B	Filter bag C	Filter bag D
Tensile strength	Excellent	Above average	Fair	Excellent
Recommended maximum temp, °F	260	275	260	220
Resistance factor	0.9	1	0.5	0.9
Cost per bag, \$	26.00	38.00	10.00	20.00
Standard size	8 in. x 16 ft	10 in. x 16 ft	1 ft x 16 ft	1 ft x 20 ft

Step 1: Eliminate from consideration bags that, on the basis of given characteristics, are unsatisfactory. Considering the operating temperature and the bag tensile strength required for a pulse jet system:

- Bag D is eliminated because its recommended maximum temperature (220°F) is below the operating temperature of 250°F.
- Bag C is also eliminated because a pulse jet fabric filter system requires the tensile strength of the bag to be at least above average.

Step 2: Determine comparative costs of the remaining bags. Total cost for each bag type is the number of bags times the cost per bag. No single individual bag type is more durable than the other.

Establish the cost per bag. From the information given in the table, the cost per bag is \$26.00 for Bag A and \$38.00 for Bag B.

Determine number of bags, N, for each type. The number of bags required, N, is the total filtering area required, divided by the filtering area per bag.

Calculate the total filter area A_t . Calculate given flow rate to actual cubic feet per minute, Q_a .

$$Q = (10,000) (250 + 460) / (60 + 460) = 13654 \text{ acfm}$$

Establish filtering capacity v_f . This is given. The A/C ratio, expressed in cubic feet per minute per square foot, is the same as the filtering velocity, which is given previously as 2.5 cfm/ft² cloth. From the information given in the table, the filtering velocity is:

$$v_f = 2.5 \text{ ft/min}$$

Calculate the total filtering cloth area, A_c , from the actual cubic feet per minute and filtering velocity determined before:

$$A_c = Q_a / v_f = 13654 / 2.5 = 5461.6 \text{ ft}^2$$

Calculate the filtering area per bag. Bags are assumed to be cylindrical; the bag area is $A = \pi Dh$, where D=bag diameter and h=bag length:

$$\text{For bag A: } A = \pi Dh = \pi (8/12) (16) = 33.5 \text{ ft}^2$$

$$\text{For bag B: } A = \pi Dh = \pi (10/12) (16) = 41.9 \text{ ft}^2$$

Determine the number of bags required, N. $N = (\text{filtering cloth area of each bag } A_c) / (\text{bag area } A)$:

$$\text{For bag A: } N = A_c / A = 5461.6 / 33.5 = 163$$

$$\text{For bag B: } N = 5461.6 / 41.9 = 130$$

Determine the total cost for each bag:

$$\text{For bag A: total cost} = (N) (\text{cost per bag}) = (163) (26.00) = \$4238$$

$$\text{For bag B: total cost} = (130) (38.00) = \$4940$$

Step 3: Select the most appropriate filter bag, considering the performance and cost. Because the total cost for bag A is less than for bag B, select bag A.

60. Determine the number of filtering bags required and cleaning frequency for a plant equipped with a fabric filter system. Operating and design data are given below.

Given:

Volumetric flow rate of the gas stream=50,000 acfm

Dust concentration=5.0 gr/ft³

Efficiency of the fabric filter system=98.0%

Filtration velocity=10 ft/min

Diameter of filtering bag=1.0 ft

Length of filtering bag=15 ft

The system is designed to begin cleaning when the pressure drop reaches 8.9 in. of water.

The pressure drop is given by:

$$\Delta p = 0.2v_f + 5c(v_f)^2 t$$

Step 1: What is the number of bags N needed? To calculate N, we need the total required surface area of the bags and the surface area of each bag.

Calculate the total required surface area of the bags A_c in square feet

$$A_c = q/v_f = 50000/10 = 5000 \text{ ft}^2$$

Calculate the surface area of each bag A, in square feet:

$$A = \pi Dh = \pi (1.0) (15) = 47.12 \text{ ft}^2$$

Calculate the required number of bags N:

$$N = A_c/A = 5000/47.12 = 106$$

Step 2: Calculate the required cleaning frequency:

$$\Delta p = 0.2 v_f + 5c (v_f)^2 t$$

Because Δp is given as 8.0 in. H₂O, the time since the bags were cleaned is calculated by solving the preceding equation:

$$5.0 \text{ gr/ft}^3 = 0.0007143 \text{ lb/ft}^3 \text{ and } \Delta p = 0.2v_f + 5c (v_f)^2 t$$

$$8.0 = (0.2) (10) + (5) (0.0007143) (10)^2 t$$

Solving for t,

$$t = 16.8 \text{ min}$$

61. An installed baghouse is presently treating a contaminated gas stream. Suddenly, some of the bags break. Estimate this baghouse system's new outlet loading.

Given:

Operation conditions of the system=60°F, 1 atm

Inlet loading=4.0 gr/acf

Outlet loading before bag failure=0.02 gr/acf

Volumetric flow rate of contaminated gas=50,000 acfm

Number of compartments=6

Number of bags per compartment=100

Bag diameter=6 in.

Pressure drop across the system=6 in. H₂O

Number of broken bags=2 bags

Assume that all the contaminated gas emitted through the broken bags is the same as that passing through the tube sheet thimble.

Step 1: Calculate the collection efficiency and penetration before the bag failures. Collection efficiency is a measure of a control device's degree of performance; it specifically refers to degree of removal of pollutants. Loading refers to the concentration of pollutants, usually in grains of pollutants per cubic foot of contaminated gas streams. Mathematically, the collection efficiency is defined as:

$$\eta = ((\text{inlet loading} - \text{outlet loading}) / (\text{inlet loading})) (100)$$

From the preceding equation, the collected amount of pollutants by a control unit is the product of collection efficiency η and inlet loading. The inlet loading minus the amount collected gives the amount discharged to the atmosphere.

Another term used to describe the performance or collection efficiency of control devices is penetration P_t :

$$P_t = 1 - \eta / 100 \text{ (fractional basis)}$$

$$P_t = 100 - \eta \text{ (percent basis)}$$

The following equation describes the effect of bag failure on baghouse efficiency:

$$P_{t1} = P_{t2} + P_{tc}$$

$$P_{tc} = 0.582(\Delta p)^{0.5} / \phi$$

$$\phi = Q / (LD^2(Y+460)^{0.5})$$

$$\eta = (\text{inlet loading} - \text{outlet loading}) / (\text{inlet loading}) = (4.0 - 0.02) / (4.0) = 99.5\%$$

Penetration is:

$$P_t = 1.0 - \eta = 0.005$$

Step 2: Calculate the bag failure parameter ϕ , a dimensionless number:

$$\phi = Q / (LD^2(T+460)^{0.5}) = 50,000 / (2)(6)^2(60+460)^{0.5} = 30.45$$

Step 3: Calculate the penetration correction P_{tc} ; this determines penetration from bag failure:

$$P_{tc} = 0.582(\Delta p)^{0.5} / \phi = 0.582 \times (6)^{0.5} / 30.45 = 0.0468$$

Step 4: Calculate the penetration and efficiency after the two bags failed. Use the results of steps 1 and 3 to calculate P_{t1} :

$$P_{t1} = P_{t2} + P_{tc} = 0.005 + 0.0468 = 0.0518$$

$$\eta^* = 1 - 0.0518 = 0.948$$

Step 5: Calculate the new outlet loading after the bag failures. Relate inlet loading and new outlet loading to the revised efficiency or penetration:

$$\text{New outlet loading} = (\text{inlet loading}) P_{t1} = (4.0)(0.0518) = 0.207 \text{ gr/acf}$$

62. A plant emits 50,000 acfm of gas containing a dust loading of 2.0 gr/ft³. A particulate control device is employed for particle capture; the dust captured from the unit is worth \$0.01/lb. Determine the collection efficiency for which the cost of power equals the value of the recovered material. Also determine the pressure drop in inches of H₂O at this condition.

Given:

Overall fan efficiency=55%

Electric power cost=\$0.06/kWh

For this control device, assume that the collection efficiency is related to the system pressure drop Δp through the equation:

$$\eta = \Delta p / (\Delta p + 5.0)$$

Step 1: Express the value of the dust collected in terms of collection efficiency η :

Amount of dust collected=(Q) (inlet loading) (η)

Note that the collected dust contains 7000 grains per pound.

The value of dust collected=50,000(ft³/min) 2 (gr/ft³) (1/7000) (lb/gr) \times 0.01(\$/lb) η =0.143 η \$/min

Step 2: Express the value of the dust collected in terms of pressure drop Δp . Recall that $\eta = \Delta p / (\Delta p + 5.0)$.

The value of dust collected=0.143 ($\Delta p / (\Delta p + 5.0)$) \$/min

Step 3: Express the cost of power in terms of pressure drop Δp :

$$Bhp = Q\Delta p / \eta' = \text{brake horsepower}$$

Cost of power= Δp (lb_v/ft²) (50,000) ((ft³/min) (1/44,200) (kWmin/ftlb_v) (1/0.55) \times (0.06) (\$/kWh) (1/60) (h/min))=0.002 Δp \$/min

Step 4: Set the cost of power equal to the value of dust collected and solve for Δp in pounds' per square foot. This represents breakeven operation. Then, convert this pressure drop to inches of H₂O. To convert from pounds per square foot to inches of H₂O, divide by 5.2.

$$(0.143) \Delta p / (\Delta p + 5) = 0.002 \Delta p$$

Solving for Δp :

$$\Delta p = 66.5 \text{ lb/ft}^2 = 12.8 \text{ in. H}_2\text{O}$$

Step 5: Calculate the collection efficiency using the calculated value of Δp .

$$\eta = 66.5 / (66.5 + 5) = 0.93 = 93.0\%$$

63. Determine capital, operating, and maintenance costs on an annualized basis for a textile dye and finishing plant (with two coal-fired stoker boilers), where a baghouse is employed for particulate control. Use the given operating, design, and economic factors.

Given:

Exhaust volumetric flow from two boilers=70,000 acfm

Overall fan efficiency=60%

Operating time=6240 h/year

Surface area of each bag=12.0 ft²

Bag type=Teflon® felt

Air-to-cloth ratio=5.81 acfm/ft²

Total pressure drop across the system=17.16 lb_f/ft²

Cost of each bag=\$75.00

Installed capital costs=\$2.536/acfm

Cost of electrical energy=\$0.03/kWh

Yearly maintenance cost=\$5000 plus yearly cost to replace 25% of the bags

Salvage value=0

Interest rate (i)=8%

Lifetime of baghouse (m)=15 yr

Annual installed capital cost (AICC)=(installed capital cost) {i (1+i)^m/((1+i)^m - 1)}

Step 1: What is the annual maintenance cost? Calculate the number of bags N:

$$N=Q/(\text{air-to-cloth ratio}) \quad (A)=(70,000)/(5.81) \quad (12)=1004 \text{ bags}$$

Calculate the annual maintenance cost in dollars per year.

$$\text{Annual maintenance cost}=\$5000/\text{year}+\text{cost of replacing 25\% of the bags each year}=\$5000 \\ \square\square (0.25) (1004) (75.00)=\$23,825/\text{year}$$

Step 2: What is the annualized installed cost (AICC)? Calculate the installed capital cost in dollars:

$$\text{Installed capital cost}=(Q) (\$2.536/\text{acfm})=(70,000) (2.536)=\$177,520$$

Calculate the AICC using the equation given previously:

$$\text{AICC}=(\text{installed capital cost}) \{i (1+i)^m/((1+i)^m - 1)\}=(177,520)\{0.08(1+0.08)^{15}/((1+0.08)^{15} - 1)\}=\$20,740/\text{yr}$$

Step 3: Calculate the operating cost in dollars per year:

$$\text{Operating cost}=Q\Delta p (\text{operating time}) (0.03/\text{kWh}/E)$$

Because 1 ft-lb/sec=0.0013558 kW,

$$\text{Operating cost}=(70,000/60) (17.16) (6240) (0.03) (0.0012558)/0.6=\$8470/\text{yr}$$

Step 4: Calculate the total annualized cost in dollars per year:

$$\text{Total annualized cost}=(\text{maintenance cost})+\text{AICC}+(\text{operating cost})=23,825+20,740+8470=\$53,035/\text{yr}$$

64. Cheeps Disposal Inc. plans to install a hazardous-waste incinerator to burn liquid and solid waste materials. The exhaust gas from the incinerator will pass through a quench spray, then into a Venturi scrubber, and finally through a packed bed scrubber. Caustic added to the scrubbing liquor will remove any HCl from the flue gas and will control the pH of the scrubbing liquor. The uncontrolled particulate emissions leaving the incinerator are estimated to be 1100 kg/h (maximum average). Local air pollution regulations state that particulate emissions must not exceed 10 kg/h. Using the following data, estimate the particulate collection efficiency of the Venturi scrubber.

Given:

Mass-median particle size (physical) d_{ps} =9.0 μm

Geometric standard deviation σ_{gm} =2.5

Particle density ρ_p =1.9 g/cm³

Gas viscosity μ_g =2.0 $\times 10^{-4}$ g/cm-sec

Gas kinematic viscosity $\nu_g=0.2 \text{ cm}^2/\text{sec}$

Gas density $\rho_g=1.0 \text{ kg/m}^3$

Gas flow rate $Q_g=15 \text{ m}^3/\text{sec}$

Gas velocity in Venturi throat $v_{gt}=9000 \text{ cm/sec}$

Gas temperature (in Venturi) $T_g=80^\circ\text{C}$

Water temperature $T_1=30^\circ\text{C}$

Liquid density $\rho_l=1000 \text{ kg/m}^3$

Liquid flow rate $Q_l=0.014 \text{ m}^3/\text{sec}$

Liquid-to-gas ratio $L/G=0.0009 \text{ L/m}^3$

Step 1: Calculate the Cunningham slip correction factor. The mass-median particle size (physical) d_{ps} is $9.0 \mu\text{m}$.

$$C_f = 1 + ((6.21 \times 10^{-4}) T) / d_{ps} = 1 + ((6.21 \times 10^{-4}) (273+80)) / 9 = 1.024$$

$$d_{pg} = d_{ps} (C_f \times \rho_p)^{0.5} = 9 \mu\text{m} (1.024 \times 1.9 \text{ g/cm}^3)^{0.5} = 12.6 \mu\text{m}$$

Note: If the particle diameter is given as the aerodynamic geometric mean diameter d_{pg} and expressed in units of μm , this step is not required.

Step 2: Calculate the droplet diameter d_d from Nukiyama and Tanasawa equation:

$$d_d = 50 / \sqrt{v_{gr}} + 91.8 (L/G)^{1.5} = 50 / ((9000 \text{ cm/sec}) + 91.8 (0.0009))^{1.5} = 0.00080 \text{ cm}$$

Step 3: Calculate the inertial parameter for the mass-median diameter K_{pg} ,

$$K_{pg} = (d_{pg})^2 v_{gt} / (9 \mu_g d_d)$$

$$K_{pg} = (12.6 \times 10^{-4} \text{ cm})^2 (9000 \text{ cm/sec}) / \{(9(2.0 \times 10^{-4} \text{ g/cm} \cdot \text{sec}) (0.008 \text{ cm}))\} = 992$$

Step 4: Calculate the Reynolds number N_{Reo} ,

$$N_{Reo} = v_{gt} d_d / \nu_g = 9000 \times 0.008 / 0.2 = 360$$

Step 5: Calculate the drag coefficient for the liquid at the throat entrance C_D

$$C_D = 0.22 + (24 / N_{Reo}) (1 + 0.15 (N_{Reo})^{0.6}) = 0.22 + (24 / 360) (1 + 0.15 (360)^{0.6}) = 0.628$$

Step 6: Now, calculate the parameter characterizing the liquid-to-gas ratio B ,

$$B = (L/G) \rho_l / (\rho_g C_D) = (0.0009) (1000 \text{ kg/m}^3) / (1.0 \text{ kg/m}^3) (0.628) = 1.43$$

Step 7: The geometric standard deviation σ_{gm} is 2.5. The overall penetration P_t^* is 0.008.

Step 8: The collection efficiency can be calculated using the equation:

$$\eta = 1 - P_t^* = 1 - 0.008 = 99.2\%$$

Step 9: Determine whether the local regulations for particulate emissions are being met. The local regulations state that the particulate emissions cannot exceed 10 kg/h. The required collection efficiency is calculated by using the equation:

$$\eta_{\text{required}} = (\text{dust}_{\text{in}} - \text{dust}_{\text{out}}) / \text{dust}_{\text{in}} = (1100 \text{ kg/h} - 10 \text{ kg/h}) / 1100 \text{ kg/h} = 99.1$$

The estimated efficiency of the Venturi scrubber is slightly higher than the required efficiency.

65. Given conditions similar to those used in the infinite throat section example estimate the cut diameter for a Venturi scrubber. The following data are approximate.

Given:

Geometric standard deviation $\sigma_{gm}=2.5$

Particle aerodynamic geometric mean diameter $d_{pg}=12.6 \mu\text{m}$

Required efficiency=99.1%

Step 1: For an efficiency of 99.1%, the overall penetration can be calculated from

$$P_t^* = 1 - \eta = 1 - 0.991 = 0.009$$

Step 2: The overall penetration is 0.009 and the geometric standard deviation is 2.5.

$$\sigma_{gm} = 2.5$$

$$(d_p)_{cut} / d_{pg} = 0.09$$

Step 3: The cut diameter $(d_p)_{cut}$ is calculated from

$$(d_p)_{cut} / d_{pg} = 0.09 \quad (12.6 \mu\text{m}) = 1.134 \mu\text{m}$$

66. A particle size analysis indicated that:

d_{gm} (geometric mean particle diameter)=12 μm

σ_{gm} (standard deviation of the distribution)=3.0

η (wet collector efficiency)=99%

If a collection efficiency of 99% were required to meet emission standards, what would the cut diameter of the scrubber need to be?

Step 1: Write the penetration (P_t) equation:

$$P_t^* = 1 - \eta = 1 - 0.99 = 0.01$$

$(d_p)_{cut} / d_{gm}$, for $P_t^* = 0.01$, and $\sigma_{gm} = 3.0$; $(d_p)_{cut} / d_{gm}$ equals 0.063. Because $d_{gm} = 12 \mu\text{m}$, the scrubber must be able to collect particles of size $0.063 \times 12 = 0.76 \mu\text{m}$ (with at least 50% efficiency) to achieve an overall scrubber efficiency of 99%.

67. Stack test results for a wet scrubber used to control particulate emissions from a foundry cupola reveal that the particulate emissions must be reduced by 85% to meet emission standards. If a 100-acfm pilot unit is operated with a water flow rate of 0.5 gal/min at a water pressure of 80 psi, what pressure drop (Δp) would be needed across a 10,000-acfm scrubber unit?

$$\alpha = 1.35$$

$$\beta = 0.621$$

Step 2: Calculate the number of transfer units N_t ,

$$\eta = 1 - \exp(-N_t)$$

$$N = \ln(1/(1 - \eta)) = \ln(1/(1 - 0.85)) = 1.896$$

Step 3: Calculate the total contacting power P_T .

$$N_t = \alpha (P_T)^\beta$$

$$1.896 = 1.35 (P_T)^{0.621}$$

$$\ln 1.404 = 0.621 (\ln P_T)$$

$$P_T = 1.73 \text{ hp} / 1000 \text{ acfm}$$

Step 4: Calculate the pressure drop Δp

$$P_T = 0.1575 \Delta p + 0.583 p_L (Q_L / Q_G)$$

$$1.73 = 0.1575 \Delta p + 0.583(80) (0.5 / 100)$$

$$\Delta p = 9.5 \text{ in. H}_2\text{O}$$

68. Calculate the throat area of a Venturi scrubber to operate at specified collection efficiency.

Given:

Volumetric flow rate of process gas stream=11,040 acfm (at 68°F)

Density of dust=187 lb/ft³

Liquid-to-gas ratio=2 gal/1000 ft³

Average particle size=3.2 μm (1.05 × 10⁻⁵ ft)

Water droplet size=48 μm (1.575 × 10⁻⁴ ft)

Scrubber coefficient k=0.14

Required collection efficiency=98%

Viscosity of gas=1.23 × 10⁻⁵ lb/ft-sec

Cunningham correction factor=1.0

Step 1: Calculate the inertial impaction parameter, ψ , from Johnstone's equation. (Johnstone's equation describes the collection efficiency of a Venturi scrubber.

$$\eta = 1 - \exp(-k (Q_L/Q_G) \psi^{0.5})$$

Step 2: From the calculated value of the preceding ψ (internal impaction parameter), back calculate the gas velocity at the Venturi throat v .

Calculate ψ :

$$\eta = 1 - \exp(-k (Q_L/Q_G) \psi^{0.5})$$

$$0.98 = 1 - \exp(-0.14 (2) \psi^{0.5})$$

Solving for ψ :

$$\psi = 195.2$$

Calculate v :

$$\psi = C_f p_p v (d_p)^2 / 18 d_d \mu$$

$$v = 18 \psi d_d \mu / C_f p_p (d_p)^2 = (18) (195.2) (1.575 \times 10^{-4}) (1.23 \times 10^{-5}) / (1) (187) (1.05 \times 10^{-5})^2 = 330.2 \text{ ft/sec}$$

Step 3: Calculate the throat area S , using gas velocity at the Venturi throat v :

$$S = (\text{volumetric flow rate}) / (\text{velocity}) = 11,040 / (60) (330.2) = 0.557 \text{ ft}^2$$

69. Calculate the overall collection efficiency of a Venturi scrubber that cleans a fly ash-laden gas stream, given the liquid-to-gas ratio, throat velocity, and particle size distribution.

Given

Liquid-to-gas ratio=8.5 gal/1000 ft³

Throat velocity=227 ft/sec

Particle density of fly ash=43.7 lb/ft³

Gas viscosity=1.5 × 10⁻⁵ lb/ft-sec

The particle size distribution data are given in the table. Use Johnstone's equation with a k value of 0.2 to calculate the collection efficiency. Ignore the Cunningham correction factor effect.

d_p , Microns	Weight, percent
<0.1	0.01

0.1-0.5	0.21
0.5-1.0	0.78
1.0-5.0	13
5.0-10.0	16
10.0-15.0	12
15.0-20.0	8
>20.0	50

Step 1: What are the parameters used in Johnstone's equation?

$$\eta = 1 - \exp(-k(Q_L/Q_G)\psi^{0.5})$$

Calculate the average droplet diameter in feet. The average droplet diameter may be calculated using the equation:

$$d_d = (16400/V) + 1.45(Q_L/Q_G)^{1.5} = (16400/272) + 1.45(8.5)^{1.5} = 96.23 \text{ microns}$$

Express the inertial impaction parameter in terms of d_p (feet):

$$\psi = C_f P_p v (d_p)^2 / 18 d_a \mu = (1)(43.7)(272)(d_p)^2 / 18(3.156 \times 10^{-4})(1.5 \times 10^{-5})$$

Express the fractional collection efficiency η_i , in terms of d_{pi} (d_p in feet):

$$\eta_i = 1 - \exp(-k(Q_L/Q_G)\psi^{0.5}) = 1 - \exp(-0.2(8.5)(1.3945 \times 10^{11} d_p^2)^{0.5})$$

Step 2: Calculate the collection efficiency for each particle size appearing in the table:

d_p , Microns	Weight, percent
<0.1	0.01
0.1-0.5	0.21
0.5-1.0	0.78
1.0-5.0	13
5.0-10.0	16
10.0-15.0	12
15.0-20.0	8
>20.0	50

For $d=0.05$ micron (1.64×10^{-7} ft), for example:

$$\eta_i = 1 - \exp(-6.348 \times 10^5 d_{pi}) = 0.0989$$

$$w_i \eta_i = 9.89 \times 10^{-4}$$

d_p , Feet	W_i Percent	η_i	$W_i \eta_i$
1.64×10^{-7}	0.01	0.0989	9.89×10^{-4}
9.84×10^{-7}	0.21	0.4645	0.0975
2.62×10^{-6}	0.78	0.8109	0.6325
9.84×10^{-6}	13	0.9981	12.98
2.62×10^{-5}	16	1	16
4.27×10^{-5}	12	1	12
5.91×10^{-5}	8	1	8
6.56×10^{-5}	50	1	50

Step 3: Calculate the overall collection efficiency:

$$\eta = \sum w_i \eta_i = 9.89 \times 10^{-4} + 0.0975 + 0.6325 + 12.98 + 16.00 + 12.00 + 8.00 + 50.00 = 99.71\%$$

70. A vendor proposes to use a spray tower on a lime kiln operation to reduce the discharge of solids to the atmosphere. The inlet loading must be reduced to meet state regulations. The vendor's design calls for a certain water pressure drop and gas pressure drop across the tower. Determine whether this spray tower will meet state regulations. If the spray tower does not meet state regulations, propose a set of operating conditions that will meet the regulations.

Given:

Gas flow rate=10,000 acfm

Water rate=50 gal/min

Inlet loading=5.0 gr/ft³

Maximum gas pressure drop across the unit=15 in. H₂O

Maximum water pressure drop across the unit=100 psi

Water pressure drop=80 psi

Gas pressure drop across the tower=5.0 in. H₂O

State regulations require a maximum outlet loading of 0.05 grains per cubic foot. Assume that the contact power theory applies.

Step 1: Calculate the collection efficiency based on the design data given by the vendor. The contact power theory is an empirical approach that relates particulate collection efficiency and pressure drop in wet scrubber systems. It assumes that particulate collection efficiency is a sole function of the total pressure loss for the unit:

$$P_T = P_G + P_L$$

$$P_G = 0.157 \Delta p$$

$$P_L = 0.583 p_L (Q_L / Q_G)$$

The scrubber collection efficiency is also expressed as the number of transfer units:

$$N_t = \alpha (P_T)^\beta = \ln(1 / (1 - \eta))$$

Calculate the total pressure loss P_T . To calculate the total pressure loss, we need the contacting power for the gas stream energy input and liquid stream energy input.

Calculate the contacting power based on the gas stream energy input P_G in hp/1000 acfm. Because the vendor gives the pressure drop across the scrubber, we can calculate P_G :

$$P_G = 0.157 \Delta p = (0.157) (5.0) = 0.785 \text{ hp/1000 acfm}$$

Calculate the contacting power based on the liquid stream energy input P_L , in horsepower per 1000 acfm.

Because the liquid inlet pressure and liquid-to-gas ratio are given, we can calculate P_L :

$$P_L = 0.583 p_L (Q_L / Q_G) = 0.583(80) (50 / 10,000) = 0.233 \text{ hp/1000 acfm}$$

Calculate the total pressure loss P_T , in horsepower per 1000 acfm:

$$P_T = P_G + P_L = 0.785 + 0.233 = 1.018 \text{ hp/1000 acfm}$$

Calculate the number of transfer units N_t :

$$N_t = \alpha (P_T)^\beta$$

The values of α and β for a lime kiln operation are 1.47 and 1.05, respectively. These coefficients have been previously obtained from field test data. Therefore,

$$N_t = \alpha (P_T)^\beta = (1.47) (1.018)^{1.05} = 1.50$$

Calculate the collection efficiency based on the design data given by the vendor:

$$N_t = \ln(1/(1 - \eta))$$

$$1.50 = \ln(1/(1 - \eta))$$

Solving for η :

$$\eta = 77.7\%$$

Step 2: Calculate collection efficiency required by state regulations. Because the inlet loading is known and the outlet loading is set by the regulations, we can readily calculate the collection efficiency:

$$\text{Collection efficiency} = ((\text{inlet loading} - \text{outlet loading}) / \text{inlet loading}) (100)$$

$$= ((5.0 - 0.05) / 5.0) (100) = 99.0\%$$

Step 3: Does the spray tower meet the regulations? No. The collection efficiency, based on the design data given by the vendor, should be higher than the collection efficiency required by the state regulations.

Step 4: Assuming the spray tower does not meet the regulations; propose a set of operating conditions that will meet the regulations. Note that the calculation procedure is now reversed. Calculate the total pressure loss P_T , using the collection efficiency required by the regulations in horsepower per 1000 acfm. Calculate the number of transfer units for the efficiency required by the regulations:

$$N_t = \ln(1/(1 - \eta)) = \ln(1/(1 - 0.99)) = 4.605$$

Calculate the total pressure loss P_T , in horsepower per 1000 acfm:

$$N_t = \alpha (P_T)^\beta$$

$$4605 = 1.47 P_T^{1.05}$$

Solving for P_T :

$$P_T = 2.96 \text{ hp}/1000 \text{ acfm}$$

Calculate the contacting power based on the gas stream energy input P_G , using a Δp of 15 in. H_2O . A pressure drop

Δp of 15 in. H_2O is the maximum value allowed by the design

$$P_G = 0.157 \Delta p = (0.157) (15) = 2.355 \text{ hp}/1000 \text{ acfm}$$

Calculate the contacting power based on the liquid stream energy input P_L :

$$P_L - P_T - P_G = 2.96 - 2.355 = 0.605 \text{ hp}/1000 \text{ acfm}$$

Calculate Q_L/Q_G in gallons per actual cubic feet, using a p_L of 100 psi:

$$P_L = 0.583 p_L (Q_L/Q_G)$$

$$Q_L/Q_G = P/0.583 p_L = 0.605 / (0.583) (100) = 0.0104$$

Determine the new water flow rate Q_L' , in gallons per minute:

$$(Q_L) = (Q_L/Q_G) (10,000 \text{ acfm}) = 0.0104 (10,000 \text{ acfm}) = 104 \text{ gal}/\text{min}$$

What is the new set of operating conditions that will meet the regulations?

$$Q_L' = 104 \text{ gal}/\text{min}$$

$$P_T = 2.96 \text{ hp}/1000 \text{ acfm}$$

71. A steel pickling operation emits 300 ppm HCl (Hydrochloric Acid), with peak values of 500 ppm, 15% of the time. The airflow is a constant 25,000 acfm at 75°F and 1 atm. Only sketchy information was submitted with the scrubber permit application

for a spray tower. We are requested to determine if the spray unit is satisfactory.

Given

Emission limit=25 ppm HCl

Maximum gas velocity allowed through the water=3 ft/sec

Number of sprays=6

Diameter of the tower=14 ft

The plans show a countercurrent water spray tower. For a very soluble gas (Henry's law constant approximately zero), the number of transfer units (N_{OG}) can be determined by the following equation:

$$N_{OG} = \ln(y_1/y_2)$$

In a spray tower, the number of transfer units N_{OG} for the first (or top) spray is about 0.7. Each lower spray has only about 60% of the N_{OG} of the spray above it. The final spray, if placed in the inlet duct, has an N_{OG} of 0.5.

The spray sections of a tower are normally spaced at 3-ft intervals. The inlet duct spray adds no height to the column.

Step 1: Calculate the gas velocity through the tower:

$$V=Q/S=Q/(\pi D^2/4)=25,000/(\pi (14)^2/4)=162.4 \text{ ft/min}$$

Step 2: Does the gas velocity meet the requirement? Yes, because the gas velocity is less than 3 ft/sec.

Step 3: Calculate the number of overall gas transfer units N_{OG} required to meet the regulation. Recall that

$$N_{OG} = \ln(y_1/y_2)$$

Use the peak value for inlet gas concentration:

$$N_{OG} = \ln(y_1/y_2) = \ln(500/25) = 3.0$$

Step 4: Determine the total number of transfer units provided by a tower with six spray sections. Remember that each lower spray has only 60% of the efficiency of the section above it (because of back mixing of liquids and gases from adjacent sections). Spray section N_{OG} values are derived accordingly:

$$\text{Top spray } N_{OG} = 0.7 \text{ (given)}$$

$$\text{2nd spray } N_{OG} = 0.7 (0.6) = 0.42$$

$$\text{3rd spray } N_{OG} = 0.42 (0.6) = 0.252$$

$$\text{4th spray } N_{OG} = 0.252 (0.6) = 0.1512$$

$$\text{5th spray } N_{OG} = 0.1512 (0.6) = 0.0907$$

$$\text{Inlet } N_{OG} = 0.5 \text{ (given)}$$

$$\text{Total } N_{OG} = 0.7 + 0.42 + 0.252 + 0.1512 + 0.0907 + 0.5 = 2.114$$

This value is below the required value of 3.0.

Step 5: Calculate the outlet concentration of gas.

$$N_{OG} = \ln(y_1/y_2)$$

$$y_1/y_2 = \exp(N_{OG}) = \exp(2.114) = 8.28$$

$$y_2 = 500/8.28 = 60.4 \text{ ppm}$$

Step 6: Does the spray tower meet the HCl regulation? Because y_2 is greater than the

required emission limit of 25 ppm, the spray unit is not satisfactory.

72. Pollution Unlimited, Inc. has submitted plans for a packed ammonia scrubber on an air stream containing NH_3 . The operating and design data are given by Pollution Unlimited. We remember approving plans for a nearly identical scrubber for Pollution Unlimited in 1978. After consulting our old files, we find all the conditions were identical except for the gas flow rate. What is our recommendation?

Given

Tower diameter=3.57 ft

Packed height of column=8 ft

Gas and liquid temperature=75°F

Operating pressure=1.0 atm

Ammonia-free liquid flow rate (inlet)=1000 lb/ft²-h

Gas flow rate=1575 acfm

Gas flow rate in the 1978 plan=1121 acfm

Inlet NH_3 gas composition=2.0 mol%

Outlet NH_3 gas composition=0.1 mol%

Air density=0.0743 lb/ft³

Molecular weight of air=29

Henry's law constant $m=0.972$

Molecular weight of water=18

Emission regulation=0.1% NH_3

Step 1: What is the number of overall gas transfer units N_{OG} ? The number of overall gas transfer units N_{OG} is used when calculating packing height requirements. It is a function of the extent of the desired separation and the magnitude of the driving force through the column (the displacement of the operating line from the equilibrium line). Calculate the gas molar flow rate G_m and liquid molar flow rate L_m , in pound-moles per square foot hour. The values of G_m and L_m are found on the Colburn chart. As mentioned earlier, this chart graphically predicts the value of N_{OG} . Calculate the cross-sectional area of the tower S , in square feet:

$$S = \pi D^2 / 4 = (\pi) (3.57)^2 / (4) = 10.0 \text{ ft}^2$$

Calculate the gas molar flow rate G_m , in pound-moles per square foot-hour:

$$G_m = Q_p / SM = (1575) (0.0743) / (10.0) (29) = 0.404 \text{ lb-mol/ft}^2\text{-min} = 24.2 \text{ lb-mol/ft}^2\text{-h}$$

Calculate the liquid molar flow rate L_m , in pound-moles per square foot-hour:

$$L_m = L / M_L = (1000) / (18) = 55.6 \text{ lb mol/ft}^2\text{-h}$$

Calculate the value of mG_m / L_m :

$$mG_m / L_m = (0.972) (24.2) / (55.6) = 0.423$$

Calculate the value of $(y_1 - mx_2) / (y_2 - mx_2)$, the abscissa of the Colburn chart:

$$(y_1 - mx_2) / (y_2 - mx_2) = (0.02 - (0.972) (0)) / (0.001 - (0.972) (0)) = 20.0$$

Determine the value of N_{OG} from the Colburn chart. From the Colburn chart, use the values of $(y_1 - mx_2) / (y_2 - mx_2)$ and mG_m / L_m to find the value of N_{OG} :

$$N_{OG} = 4.3$$

Step 2: What is the height of an overall gas transfer unit H_{OG} ? The height of an overall gas transfer unit H_{OG} is also used to calculate packing height requirements. H_{OG} values in air

pollution are almost always based on experience. H_{OG} is a strong function of solvent viscosity and difficulty of separation, increasing with increasing values of both.

Calculate the gas mass velocity G , in pounds per square foot-hour:

$$G = pQ/S = (1575) (0.0743) / 10.0 = 702 \text{ lb/ft}^2\text{-h}$$

H_{OG} value is 2.2 ft

Step 3: What is the required packed column height Z , in feet?

$$Z = (N_{OG}) (H_{OG}) = (4.3) (2.2) = 9.46 \text{ ft}$$

Step 4: Compare the packed column height of 8 ft specified by Pollution Unlimited, Inc. to the height calculated previously. What is the recommendation? The submission is disapproved because the calculated height (9.46 ft) is higher than that (8 ft) proposed by the company.

73. A packed column is designed to absorb ammonia from a gas stream. Given the operating conditions and type of packing (see below), calculate the height of packing and column diameter.

Given

Gas mass flow rate=5000 lb/h

NH_3 concentration in inlet gas stream=2.0 mol%

Scrubbing liquid=pure water

Packing type=1-in. Raschig rings

Packing factor, $F=160$

HOG of the column=2.5 ft

Henry's law constant $m=1.20$

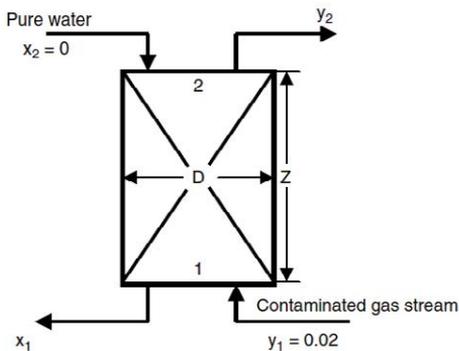
Density of gas (air)=0.075 lb/ft³

Density of water=62.4 lb/ft³

Viscosity of water=1.8 cp

Generalized flooding and pressure drop correction graph

The unit operates at 60% of the flooding gas mass velocity; the actual liquid flow rate is 25% more than the minimum and 90% of the ammonia must be collected to meet state regulations.



- Z = packed column height
- D = column diameter
- y_1 = inlet gas composition
- y_2 = outlet gas composition
- x_1 = outlet liquid composition
- x_2 = inlet liquid composition

Step 1: What is the number of overall gas transfer units N_{OG} ? Remember that the height of packing Z is given by:

$$Z=(N_{OG}) (H_{OG})$$

Because H_{OG} is given, we only need N_{OG} to calculate Z . N_{OG} is a function of the liquid and gas flow rates; however, it is usually available for most air pollution applications. What is the equilibrium outlet liquid composition x_1 and the outlet gas composition y_2 for 90% removal? Recall that we need the inlet and outlet concentrations (mole fractions) of both streams to use the Colburn chart.

Calculate the equilibrium outlet concentration x_1^* at $y_1=0.02$. According to Henry's law, x_1^* at y_1/m , the equilibrium outlet liquid composition is needed to calculate the minimum L_m/G_m :

$$x_1^*=y_1/m=(0.02)/(1.20)=0.0167$$

Calculate y_2 for 90% removal. Because state regulations require the removal of 90% of NH_3 , by material balance, 10% NH_3 will remain in the outlet gas stream:

$$y_2=(0.1y_1)/((1 - y_1) (0.1) y_1)$$

$$(0.1) (0.02)/((1 - 0.02)+(0.1) (0.02))=0.00204$$

Determine the minimum ratio of molar liquid flow rate to molar gas flow rate $(L_m/G_m)_{min}$ by a material balance. Material balance around the packed column:

$$G_m (y_1-y_2)=L_m (x_1^* - x_2)$$

$$(L_m/G_m)_{min}=(y_1 - y_2)/(x_1^* - x_2)=(0.02 - 0.00204)/(0.0167 - 0)=1.08$$

Calculate the actual ratio of molar liquid flow rate to molar gas flow rate (L_m/G_m) . Remember that the actual liquid flow rate is 25% more than the minimum based on the given operating conditions:

$$(L_m/G_m)=1.25 (L_m/G_m)_{min}=(1.25)(1.08)=1.35$$

Calculate the value of $(y_1 - mx_2)/(y_2 - mx_2)$, the abscissa of the Colburn chart:

$$(y_1-mx_2)/(y_2 - mx_2)=((0.02) - (1.2) (0))/((0.00204) - (1.2) (0))=9.80$$

Calculate the value of mG_m/L_m :

Even though the individual values of G_m and L_m are not known, the ratio of the two has been previously calculated:

$$mG_m/L_m=(1.2)/(1.35)=0.889$$

Determine number of overall gas transfer units N_{OG} from the Colburn chart using the values calculated previously (9.80 and 0.899). From the Colburn chart $N_{OG}=6.2$.

Step 2: Calculate the height of packing Z :

$$Z=(N_{OG}) (H_{OG})=(6.2) (2.5)=15.5 \text{ ft}$$

Step 3: What is the diameter of the packed column? The actual gas mass velocity must be determined. To calculate the diameter of the column, we need the flooding gas mass velocity. The mass velocity is obtained by dividing the mass flow rate by the cross-sectional area.

Calculate the flooding gas mass velocity G_f .

$$(L/G) (p/p_L)^{0.5}=(L_m/G_m) (18/29) (p/p_L)^{0.5}=(1.35) (18/29) (0.075/62.4)^{0.5}=0.0291$$

Determine the value of the ordinate at the flooding line using the calculated value of the abscissa:

$$G^2 F\psi (\mu_i)/p_L p_{gc} = 0.19$$

Solve the abscissa for the flooding gas mass velocity G_f , in pounds per square foot-second. The G value becomes G_f for this case. Thus,

$$G_{f_i} (0.19 (p_L p_{gc}) / (F\psi (\mu_i)^{0.2}))^{0.5} = ((0.19) (62.4) (0.075) (32.2) / (160) (1) (1.8)^{0.2})^{0.5}$$

Calculate the actual gas mass velocity G_{act} , in pounds per square foot-second:

$$G_{act} = 0.6 G_f = (0.6) (0.400) = 864 \text{ lb/ft}^2\text{-h}$$

Calculate the diameter of the column in feet:

$$S (\text{mass flow rate of gas stream}) / G_{act} = 5000 / G_{act}$$

$$S = \pi D^2 / 4$$

$$\pi D^2 / 4 = 5000 / G_{act}$$

$$D = \sqrt{(4(5000)) / (\pi G_{act})} = 2.71 \text{ ft}$$

74. A power plant pumps 25 ft³/sec from a stream with a flow of 180 ft³/sec. The discharge of the plant's ash pond is 22 ft³/sec. The boron concentrations for upstream water and effluent are 0.053 and 8.7 mg/L, respectively. Compute the boron concentration in the stream after complete mixing.

$$C_d = \frac{Q_s C_s + Q_w C_w}{Q_s + Q_w} = \frac{(180 - 25)(0.053) + 22 \times 8.7}{(180 - 25) + 22} = 1.13 \text{ mg/L}$$

75. The cross-section areas at river miles 63.5, 64.0, 64.5, 65.0, and 65.7 are, respectively, 270, 264, 263, 258, 257, and 260 ft² at a surface water elevation. The average flow is 32.3 ft³/sec. Find the time of travel for a reach between river miles 63.5 and 65.7.

Step 1: Find the area in the reach:

Step 2: Find volume:

$$\text{Distance of the reach} = (65.7 - 63.5) \text{ mi} = 2.2 \text{ miles} \times 5280 \text{ ft/mi} = 11,616 \text{ ft}$$

$$V = 262 \text{ ft}^2 \times 11,616 \text{ ft} = 3,043,392 \text{ ft}^3$$

Step 3: Find t:

$$t = V/Q \times 1/86,400 = 1.1 \text{ days}$$

76. Calculate DO saturation concentration for water temperature at 0, 10, 20, and 30°C, assuming $\beta=1.0$.

A. at T=0°C

$$DO_{sat} = 14.652 - 0 + 0 - 0 = 14.652 \text{ mg/L}$$

B. at T=10°C

$$DO_{sat} = 14.652 - 0.41022 \times 10 + 0.0079910 \times 10^2 - 0.000077774 \times 10^3 = 11.27 \text{ mg/L}$$

C. at T=20°C

$$DO_{sat} = 14.652 - 0.41022 \times 20 + 0.0079910 \times 20^2 - 0.000077774 \times 20^3 = 9.02 \text{ mg/L}$$

D. at T=30°C

$$DO_{sat} = 14.652 - 0.41022 \times 30 + 0.0079910 \times 30^2 - 0.000077774 \times 30^3 = 7.44 \text{ mg/L}$$

77. Find the correction factor of DO_{sat} value for water at 640 ft above the MSL and air temperature of 25°C. What is DO_{sat} at a water temperature of 20°C?

Step 1:

$$f = \frac{2116.8 - (0.08 - 0.000115A)E}{2116.8} = \frac{2116.8 - (0.08 - 0.000115 \times 25)640}{2116.8} = 0.977$$

Step 2: Compute DO_{sat} T=20°C.

$$DO_{sat} = 9.02 \text{ mg/L}$$

With an elevation correction factor of 0.977

$$DO_{sat} = 9.02 \text{ mg/L} \times 0.977 = 8.81 \text{ mg/L}$$

78. Determine BOD, milligrams per liter, given the following data:

- Initial DO=8.2 mg/L
- Final DO=4.4 mg/L
- Sample size=5 mL

$$BOD = \frac{(8.2 - 4.4)}{5} = 228 \text{ mg / L}$$

79. A series of seed dilutions were prepared in 300-mL BOD bottles using seed material (settled raw wastewater) and unseeded dilution water. The average BOD for the seed material was 204 mg/L. One milliliter of the seed material was also added to each bottle of a series of sample dilutions. Given the data for two samples in the following table, calculate the seed correction factor (SC) and BOD of the sample.

Bottle #	mL sample	mL Seed/bottle	DO Initial	Mg/L Final	Depletion, mg/L
12	50	1	8.0	4.6	3.4
13	75	1	7.7	3.9	2.8

Step 1: Calculate the BOD of each milliliter of seed material.

$$BOD / \text{mL of seed} = \frac{204 \text{ mg / L}}{300 \text{ mg / L}} = 0.68 \text{ mg / L BOD / mL seed}$$

Step 2: Calculate the SC factor:

$$SC = 0.68 \text{ mg/L BOD/mL seed} \times 1 \text{ mL seed/bottle} = 0.68 \text{ mg/L}$$

Step 3: Calculate the BOD of each sample dilution:

$$BOD, \text{mg / L, Bottle\#12} = \frac{3.4 - 0.68}{50 \text{ mL}} \times 300 = 16.3 \text{ mg / L}$$

$$BOD, \text{mg / L, Bottle\#13} = \frac{3.8 - 0.68}{75 \text{ mL}} \times 300 = 12.5 \text{ mg / L}$$

Step 4: Calculate reported BOD:

$$\text{Reported BOD} = (16.3 + 12.5) / 2 = 14.4 \text{ mg/L}$$

80. Calculate the oxygen deficit in a stream after pollution. Use the following equation and parameters for a stream to calculate the oxygen deficit D in the stream after pollution.

$$D = \frac{K_1 L_A}{K_2 - K_1} [e^{-K_1 t} - e^{-K_2 t}] + D_A e^{-K_2 t} = \frac{0.280 \times 22}{0.550 - 0.280} [e^{-0.280 \times 2.13} - e^{-0.550 \times 2.13}] + 2e^{-0.550 \times 2.13} = 6.16 \text{ mg/L}$$

81. Calculate deoxygenating constant K_1 for a domestic sewage with BOD_5 , 135 mg/L and BOD_{21} , 400 mg/L.

$$K_1 = \frac{-\log\left(1 - \frac{BOD_5}{BOD_{21}}\right)}{t} = \frac{-\log\left(1 - \frac{135}{400}\right)}{5} = 0.361 / \text{day}$$

82. A pond has a shoreline length of 8.60 miles; the surface area is 510 acres, and its maximum depth is 8.0 ft. The areas for each foot depth are 460, 420, 332, 274, 201, 140, 110, 75, 30, and 1. Calculate the volume of the lake, shoreline development index, and mean depth of the pond.

Step 1: Compute volume of the pond:

$$V = \sum_{i=0}^n h / 3 (A_i + A_{i+1} + \sqrt{A_i \times A_{i+1}})$$

$$= (1/3) \left[\begin{aligned} & (510 + 460 + \sqrt{510 \times 460}) + (460 + 420 + \sqrt{460 \times 420}) \\ & + (420 + 332 + \sqrt{420 \times 332}) + (332 + 274 + \sqrt{332 \times 274}) \\ & + (274 + 201 + \sqrt{274 \times 201}) + (201 + 140 + \sqrt{201 \times 140}) \\ & + (140 + 110 + \sqrt{140 \times 110}) + (110 + 75 + \sqrt{110 \times 75}) \\ & + (75 + 30 + \sqrt{75 \times 30}) + (30 + 1 + \sqrt{30 \times 0}) \end{aligned} \right] = 2274 \text{ acre-ft}$$

Step 2: Compute shoreline development index:

$$D_L = \frac{L}{2\sqrt{\pi A}} = \frac{8.60 \text{ miles}}{2\sqrt{\pi \times 0.7969 \text{ sq.mi}}} = 2.72$$

Step 3: Compute mean depth:

$$\text{Hydraulic gradient, } I = \frac{h_1 - h_2}{L} = \frac{120 - 110}{2200} = 0.0045$$

83. If an aquifer's thickness is 60 ft, estimate the permeability of the aquifer with transmissibility of 30,000 gpm/ft.

$$K = T/b = (30,000 \text{ gpm/ft}) / 60 \text{ ft} = 500 \text{ gpm/ft}^2$$

84. An irrigation ditch runs parallel to a pond; they are 2200 ft apart. A pervious formation of 40-ft average thickness connects them. Hydraulic conductivity and porosity of the pervious formation are 12 ft/day and 0.55, respectively. The water level in the ditch is at an elevation of 120 ft and 110 ft in the pond. Determine the rate of seepage from the channel to the pond.

$$\text{Hydraulic gradient, } I = \frac{h_1 - h_2}{L} = \frac{120 - 110}{2200} = 0.0045$$

For each 1 ft width:

$$A = 1 \times 40 = 40 \text{ ft}^2$$

$$Q = (12 \text{ ft/day}) (0.0045) (40 \text{ ft}^2) = 2.16 \text{ ft}^3/\text{day}/\text{ft width}$$

$$\text{Seepage velocity, } v = \frac{K(h_1 - h_2)}{nL} = \frac{(12)(0.0045)}{0.55} = 0.098 \text{ ft/day}$$

85. The static water level for a well is 70 ft. If the pumping water level is 90 ft, what is the drawdown?

$$\text{Drawdown, ft} = \text{Pumping Water Level, ft} - \text{Static Water Level, ft} = 90 \text{ ft} - 70 \text{ ft} = 20 \text{ ft}$$

86. The static water level of a well is 122 ft. The pumping water level is determined using the sounding line. The air pressure applied to the sounding line is 4.0 psi, and the length of the sounding line is 180 ft. What is the drawdown?

First, calculate the water depth in the sounding line and the pumping water level:

$$\text{Water Depth in Sounding Line} = (4.0 \text{ psi}) (2.31 \text{ ft/psi}) = 9.2 \text{ ft}$$

$$\text{Pumping Water Level} = 180 \text{ ft} - 9.2 \text{ ft} = 170.8 \text{ ft}$$

Then, calculate drawdown:

$$\text{Drawdown, ft} = \text{Pumping Water Level, ft} - \text{Static Water Level, ft} = 170.8 \text{ ft} - 122 \text{ ft} = 48.8 \text{ ft}$$

87. Once the drawdown level of a well stabilized, operators determined that the well produced 400 gal during the 5-min test. What is the well yield in gpm?

$$\text{Well Yield, gpm} = \frac{\text{Gallons Produced}}{\text{Duration of Test, min}} = \frac{400 \text{ gallons}}{5 \text{ min}} = 80 \text{ gpm}$$

88. During a 5-min test for well yield, a total of 780 gal are removed from the well. What is the well yield in gallons per minute? in gallons per hour?

$$\text{Well Yield, gpm} = \frac{\text{Gallons Produced}}{\text{Duration of Test, min}} = \frac{780 \text{ gallons}}{5 \text{ min}} = 156 \text{ gpm}$$

Then convert gallons per minute flow to gallons per hour flow:

$$(156 \text{ gal/min}) (60/\text{hr}) = 9360 \text{ gph}$$

89. A well produces 260 gpm. If the drawdown for the well is 22 ft, what is the specific yield in gallons per minute per foot, and what is the specific yield in gallons per minute per foot of drawdown?

$$\text{Specific Yield, gpm/ft} = \frac{\text{Well Yield, gpm}}{\text{Drawdown, ft}} = \frac{260 \text{ gpm}}{22 \text{ ft}} = 11.8 \text{ gpm/ft}$$

90. The yield for a particular well is 310 gpm. If the drawdown for this well is 30 ft, what is the specific yield in gallons per minute per foot of drawdown?

$$\text{Specific Yield, gpm/ft} = \frac{\text{Well Yield, gpm}}{\text{Drawdown, ft}} = \frac{310 \text{ gpm}}{30 \text{ ft}} = 10.3 \text{ gpm/ft}$$

91. A new well is to be disinfected with chlorine at a dosage of 50 mg/L. If the well casing diameter is 8 in. and the length of the water-filled casing is 110 ft, how many pounds of chlorine will be required?

First, calculate the volume of the water-filled casing:

$$(0.785) (.67) (67) (110 \text{ ft}) (7.48 \text{ gal/ft}^3) = 290 \text{ gallons}$$

Then, determine the pounds of chlorine required, using the milligrams-per-liter to pounds equation:

$$\text{Chlorine, lb} = (\text{chlorine, mg/L}) (\text{Volume, MG}) (8.34 \text{ lb/gal})$$

$$(50 \text{ mg/L}) (0.000290 \text{ MG}) (8.34 \text{ lb/gal}) = 0.12 \text{ lb Chlorine}$$

92. The static water level of a pump is 100 ft. The well drawdown is 26 ft. If the gauge reading at the pump discharge head is 3.7 psi, what is the total pumping head?

Total Pumping Head, ft = Pumping Water Level, ft + Discharge Head, ft

$$= (100 \text{ ft} + 26 \text{ ft}) + (3.7 \text{ psi}) (2.31 \text{ ft/psi}) = 126 \text{ ft} + 8.5 \text{ ft} = 134.5 \text{ ft}$$

93. The pumping water level for a well pump is 150 ft, and the discharge pressure measured at the pump discharge centerline is 3.5 psi. If the flow rate from the pump is 700 gpm, what is the water horsepower?

First, calculate the field head. The discharge head must be converted from psi to ft:

$$(3.5 \text{ psi}) (2.31 \text{ ft/psi}) = 8.1 \text{ ft}$$

The water horsepower is therefore:

$$150 \text{ ft} + 8.1 \text{ ft} = 158.1 \text{ ft}$$

The water horsepower can now be determined:

$$= \frac{150 \text{ ft} + 8.1 \text{ ft}}{33000 \text{ ft} - \text{lb} / \text{min}} = 28 \text{ whp}$$

94. The pumping water level for a pump is 170 ft. The discharge pressure measured at the pump discharge head is 4.2 psi. If the pump flow rate is 800 gpm, what is the water horsepower?

First, determine the field head by converting the discharge head from psi to ft:

$$(4.2 \text{ psi}) (2.31 \text{ ft/psi}) = 9.7 \text{ ft}$$

Now, calculate the field head:

$$170 \text{ ft} + 9.7 \text{ ft} = 179.7 \text{ ft}$$

And then calculate the water horsepower:

$$\text{whp} = \frac{(179.7 \text{ ft})(800 \text{ gpm})}{3960} = 36 \text{ whp}$$

95. A deep-well vertical turbine pump delivers 600 gpm. If the lab head is 185 ft and the bowl efficiency is 84%, what is the bowl horsepower?

$$\text{Bowl bhp} = \frac{(\text{Bowl Head, ft})(\text{Capacity, gpm})}{(3960)(\text{Bowl Efficiency})} = \frac{(185 \text{ ft})(600 \text{ gpm})}{(3960)(84.0)} = 33.4 \text{ bowl bhp}$$

96. The bowl brake horsepower is 51.8 bhp. If the 1-in. diameter shaft is 170 ft long and is rotating at 960 rpm with a shaft friction loss of 0.29 hp loss per 100 ft, what is the field bhp?

Before you can calculate the field bhp, factor in the shaft loss:

$$\frac{(0.29 \text{ hp loss})(170 \text{ ft})}{100}$$

Now determine the field bhp:

$$\text{Field bhp} = \text{Bowl bhp} + \text{Shaft Loss, hp} = 51.8 \text{ bhp} + 0.5 \text{ hp} = 52.3 \text{ bhp}$$

97. The field horsepower for a deep-well turbine pump is 62 bhp. If the thrust bearing loss is 0.5 hp and the motor efficiency is 88%, what is the motor input horsepower?

$$Mhp = \frac{\text{Field (total) bhp}}{\text{Motor Efficiency}} = \frac{62 \text{ bhp} + 0.5 \text{ hp}}{0.88} = 71 \text{ mhp}$$

98. Given the following data, calculate the field efficiency of the deep-well turbine pump:

- Field head — 180 ft
- Capacity — 850 gpm
- Total bhp — 61.3 bhp

$$\text{Field Efficiency, \%} = \frac{(\text{Field Head, ft})(\text{Capacity, gpm})}{(3960)(\text{Total bhp})} \times 100 = \frac{(180 \text{ ft})(850 \text{ gpm})}{(3960)(61.3 \text{ bhp})} = 63\%$$

99. Given the following data, determine the mass balance of the biological process and the appropriate waste rate to maintain current operating conditions.

Process	Extended aeration (no primary)	
Influent	Flow	1.1 MGD
	BOD	220 mg/L
	TSS	240 mg/L
Effluent	Flow	1.5 MGD
	BOD	18 mg/L
	TSS	22 mg/L
Waste	Flow	24,000 gpd
	TSS	8710 mg/L

$$\text{BOD in} = 220 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 = 2018 \text{ lb/day}$$

$$\text{BOD out} = 18 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 = 165 \text{ lb/day}$$

$$\text{BOD Removed} = 2018 \text{ lb/day} - 165 \text{ lb/day} = 1853 \text{ lb/day}$$

$$\text{Solids Produced} = 1853 \text{ lb/day} \times 0.65 \text{ lb/lb BOD} = 1204 \text{ lb solids/day}$$

$$\text{Solids Out, lb/day} = 22 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 = 202 \text{ lb/day}$$

$$\text{Sludge Out, lb/day} = 8710 \text{ mg/L} \times 0.024 \text{ MGD} \times 8.34 = 1743 \text{ lb/day}$$

$$\text{Solids Removed, lb/day} = (202 \text{ lb/day} + 1743 \text{ lb/day}) = 1945 \text{ lb/day}$$

$$\text{Mass Balance} = \frac{(1204 \text{ lb Solids / day} - 1945 \text{ lb / day}) \times 100}{1204 \text{ lb / day}} = 62\%$$

The mass balance indicates:

The sampling points, collection methods, and/or laboratory testing procedures are producing non-representative results.

The process is removing significantly more solids than is required. Additional testing should be performed to isolate the specific cause of the imbalance.

To assist in the evaluation, the waste rate based upon the mass balance information can be calculated.

$$\text{Waste, GPD} = \frac{\text{Solids Produced, lb / day}}{(\text{Waste TSS, mg / L} \times 8.34)} = \frac{1204 \text{ lb / day} \times 1000000}{8710 \text{ mg / L} \times 8.34} = 1675 \text{ gpd}$$

100. A dual medium filter is composed of 0.3 m anthracite (mean size of 2.0 mm) placed over a 0.6-m layer of sand (mean size 0.7 mm) with a filtration rate of 9.78 m/h. Assume the grain sphericity is $\psi=0.75$ and a porosity for both is 0.42. Although normally taken from the appropriate table at 15°C, we provide the head loss data of the filter at $1.131 \times 10^{-6} \text{ m}^2 \text{ sec}$.

Step 1: Determine head loss through anthracite layer using the Kozeny equation.

$$\frac{h}{L} = \frac{k\mu(1-\varepsilon)^2}{gpe^3} \left(\frac{A}{V}\right)^2 u$$

$$h = 6 \times \frac{1.131 \times 10^{-6}}{9.81} \times \frac{1-0.42^2}{0.42^3} \times \left(\frac{8}{0.002}\right)^2 (0.00272)(0.2) = 0.0410 \text{ m}$$

Step 2: Compute the head loss passing through the sand.

$$h = 5 \times \frac{1.131 \times 10^{-6}}{9.81} \times \frac{1-0.58^2}{0.42^3} \times \left(\frac{8}{0.007}\right)^2 (0.00272)(0.2) = 0.5579 \text{ m}$$

Step 3: Compute total head loss:

$$h = 0.0410 \text{ m} + 0.5579 \text{ m} = 0.599 \text{ m}$$

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