

INTRODUCTION TO ENVIRONMENTAL ENGINEERING**HOMEWORK #1 – SOLUTIONS**

1. (10 points) Read the article by the Vermont Department of Health on air quality in offices, posted on the internet at

http://healthvermont.gov/enviro/indoor_air/air_office.aspx

and focus on the 11 recommendations made in the last section “What can be done...”.

a. (6 points) Which of these recommendations address pollution prevention and which deal with treatment of existing pollution?

b. (4 points) Which in your opinion are the two most effective strategies to avoid air pollution in offices that are already in existence (as opposed to planning and building new offices)?

(a) The article lists 11 measures that can be implemented. Sorting them out by prevention versus treatment we have:

Pollution prevention measures:

1. Reduce or eliminate the potential source or activity.
2. Choose the least toxic product when you have a choice between two products that produce the same cleaning results.
3. Store chemicals properly in an area not normally occupied by people, and mechanically vent the storage area directly to the outside of the building.
4. Read and follow directions for use on the label. Do not mix any cleaning products unless directed on the product label.
5. Control exposures at the source before indoor air becomes contaminated.
6. Keep office setting and building in good repair.
7. Limit the use of carpeting.

Pollution treatment measures:

1. Increase ventilation (fresh air).
2. Have the general air movement and introduction of fresh air be from areas of lower levels of contamination and into areas of potentially higher levels of contamination.
3. Filter the air before it is inhaled.
4. Stop or reduce pollutant pathways. Physically separate areas of occupancy from areas where high levels of pollutants may be generated.

(b) Two most effective strategies.

The rational approach is to prefer preventative measures over treatment measures. Thus, the two best strategies ought to be selected from the first group of 7 pollution prevention measures.

Of those 7 measures, the first 2 seem to be those that get most to the core of the problem. The two most effective strategies are therefore:

1. Reduce or eliminate the potential source or activity.
2. Choose the least toxic product when you have a choice between two products that produce the same cleaning results.

2. (10 points) (Mihelcic & Zimmerman, page 49, Problem 2.2, 1st half) A water sample contains 10 mg NO₃⁻/L. What is the concentration in (a) ppm on a mass basis, and (b) moles/L?

a)

1 L water = 0.997 kg water. Thus,

$$\frac{10 \text{ mg} / L}{0.997 \text{ kg} / L} = \frac{10 \times 10^{-3} \text{ g} / L}{0.997 \times 10^3 \text{ g} / L} = 1.003 \times 10^{-5} = 10.03 \times 10^{-6} = 10.03 \text{ ppm}$$

Note: Ok, if student uses 1 kg per L for water. Solution is then 10 ppm of NO₃⁻.

b)

Molecular weight of NO₃⁻ = 14x1 + 16x3 = 62 grams per mole

Thus,

$$\frac{10 \text{ mg}}{L} \times \frac{1 \text{ g}}{1,000 \text{ mg}} \times \frac{1 \text{ mole}}{62 \text{ g}} = \boxed{1.6 \times 10^{-4} \text{ moles NO}_3^- / L}$$

3. (5 points) (Mines & Lackey, page 31, Problem 2.16) Assume the discharge from a wastewater treatment plant has a flow of 30 Mgd (million gallons per day) with a solids concentration of 5 mg/L. Determine the mass flow rate of solids in lb_m/day .

Since the concentration of solids are given in metric units, let us begin by converting the wastewater flow rate in metric units, passing from gallons to liters:

$$Q = 30 \times 10^6 \text{ gallons/day} = \frac{3.78 \text{ L}}{\text{gallon}} \times \frac{30 \times 10^6 \text{ gallons}}{\text{day}} = 113.4 \times 10^6 \frac{\text{L}}{\text{day}}$$

At $c = 5 \text{ mg/L}$, the amount of solids moving with this flow rate is

$$cQ = \frac{5 \text{ mg}}{\text{L}} \times \frac{113.4 \times 10^6 \text{ L}}{\text{day}} = 567.0 \times 10^6 \frac{\text{mg}}{\text{day}} = 567.0 \frac{\text{kg}}{\text{day}}$$

All that is left to be done now is to convert the kilograms in to pounds:

$$\frac{2.205 \text{ lb}}{\text{kg}} \times \frac{567.0 \text{ kg}}{\text{day}} = 1,250. \frac{\text{lb}}{\text{day}}$$

4. (5 points) (Mines & Lackey, page 31, Problem 2.17) Consider a wastewater treatment cell having a length of 100 ft, width of 20 ft, and depth of 20 ft. If the flow into the cell is 50 ft³/min, calculate the residence time of the treatment cell.

The volume of the treatment cell is the product of its three dimensions:

$$V = L W H = (100 \text{ ft})(20 \text{ ft})(20 \text{ ft}) = 40,000 \text{ ft}^3.$$

The residence time is volume divided by flow rate:

$$\theta = \frac{V}{Q} = \frac{40,000 \text{ ft}^3}{50 \text{ ft}^3 / \text{min}} = 800 \text{ min} = 13 \text{ hours } 20 \text{ min}.$$

5. (5 points) (Mines & Lackey, page 58, Problem 3.8) Determine the volume in cubic feet occupied by 120 pounds of carbon dioxide at 1.5 atm and 40°C.

First, let us convert the mass of carbon dioxide from pounds to grams, because that will help when we invoke the molecular weight:

$$m = 120 \text{ lb} \times \frac{\text{kg}}{2.205 \text{ lb}} \times \frac{1000 \text{ g}}{\text{kg}} = 54,422 \text{ g}$$

The molecular weight of carbon dioxide (CO₂) is

$$MW = 1 \times 12 + 2 \times 16 = 44 \text{ g / mole}$$

Thus, in our given amount of CO₂, we have

$$n = \frac{m}{MW} = \frac{54,422 \text{ g}}{44 \text{ g / mole}} = 1,237. \text{ moles}$$

Now, using the ideal-gas law $PV = nRT$, we can pass from number of moles n to occupied volume V :

$$\begin{aligned} V &= \frac{nRT}{P} = \frac{(1,237. \text{ moles})(8.206 \times 10^{-5} \text{ atm} \cdot \text{m}^3 / \text{moles} \cdot \text{K})(273.15 + 40 \text{ K})}{(1.5 \text{ atm})} \\ &= 21.19 \text{ m}^3. \end{aligned}$$

Finally, we convert the cubic meters into cubic feet:

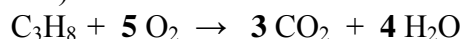
$$V = 21.19 \text{ m}^3 \times \left(\frac{1 \text{ ft}}{0.3048 \text{ m}} \right)^3 = 21.19 \text{ m}^3 \times 35.315 \frac{\text{ft}^3}{\text{m}^3} = 748.3. \text{ ft}^3.$$

6. (10 points) Consider the following reaction representing the combustion of propane:



- (2 points) Balance the equation.
- (2 points) How many moles of oxygen are required to burn 1 mole of propane?
- (3 points) How many grams of oxygen are required to burn 100 g of propane?
- (3 points) Under standard conditions (temperature of 25°C, pressure of 1 atmosphere, and oxygen concentration equal to 20% on a volume basis), what volume of air is required to burn 100 g of propane?

a. (2 points)



b. (2 points)

From the equation above, we immediately note that it takes 5 moles of oxygen (O_2) to burn 1 mole of propane (C_3H_8).

c. (3 points)

To answer this, we first need to determine the molecular weights of both propane and oxygen:

Propane: $\text{C}_3\text{H}_8 \rightarrow 3 \times 12 + 8 \times 1 = 44$ grams/mole

Oxygen: $\text{O}_2 \rightarrow 2 \times 16 = 32$ grams/mole

In 100 grams of propane, there are therefore

$$\frac{100 \text{ grams}}{44 \text{ grams/mole}} = 2.273 \text{ moles of } \text{C}_3\text{H}_8$$

Each mole of propane demands 5 moles of oxygen. The necessary number of moles of oxygen is then:

$$5 \times 2.273 \text{ moles} = 11.364 \text{ moles of } \text{O}_2$$

The corresponding mass of oxygen is:

$$11.364 \text{ moles} \times \frac{32 \text{ grams}}{\text{mole}} = 363.6 \text{ grams of } \text{O}_2$$

d. (3 points)

Oxygen behaves as an ideal gas: $PV = nRT$. This allows us to determine the volume V of oxygen occupied by $n = 11.364$ moles. With:

$T = 25^\circ\text{C} = 298 \text{ K}$ standard (absolute) temperature

$P = 1 \text{ atm}$ standard pressure

we have:

$$V = \frac{nRT}{P} = \frac{(11.364 \text{ moles})(0.08205 \text{ atm} \cdot \text{L/mole} \cdot \text{K})(298 \text{ K})}{(1 \text{ atm})} = 277.9 \text{ L of } \text{O}_2$$

Since oxygen is only 20% of air on a volume basis, the amount of air needed is

$$\frac{277.9 \text{ L of } O_2}{0.20} = 1,389 \text{ L of air} = 1.39 \text{ m}^3 \text{ of air}$$

7. (10 points) (Mihelcic & Zimmerman, page 155, Problem 4.13) A 1.0×10^6 gallon reactor is used in a sewage-treatment plant. The influent concentration is 100 mg/L, the effluent concentration is 25 mg/L, and the flow rate through the reactor is 500 gal/min.

(a) What is the first-order rate constant for decay of BOD in the reactor? Assume that the reactor can be modeled as a CMFR. Report your answer in units of per hour.

(b) Assume that the reactor should be modeled as a PFR with first-order decay, *not* as a CMFR. In that case, what must the first-order decay rate constant be within the PFR reactor?

(c) It has been determined that the outlet concentration is too high, so the residence time in the reactor must be doubled. Assuming all other variables remain constant, what must be the volume of the new CMFR?

a)

We are given:

$$V = 1.0 \times 10^6 \text{ gal}, C_{in} = 100 \text{ mg/L}, C_{out} = 25 \text{ mg/L}, Q = 500 \text{ gal/min.}$$

Assuming steady state conditions, the mass balance on BOD in the CMFR is given as follows:

$$\frac{dm}{dt} = m_{in} - m_{out} - m_{rxn}$$

$$0 = QC_{in} - QC_{out} - Vkc$$

$$C = C_{out}$$

$$k = \frac{QC_{in} - QC_{out}}{VC_{out}} = \frac{Q(C_{in} - C_{out})}{VC_{out}} = \frac{(500 \text{ gal/min})(100 \text{ mg/L} - 25 \text{ mg/L})}{(1.0 \times 10^6 \text{ gal})(25 \text{ mg/L})} \times 60 \frac{\text{min}}{\text{h}}$$

$$\boxed{k = 0.090 / \text{h}}$$

b)

$$C_t = C_{in} \times e^{-kt}$$

$$\frac{dC}{dt} = -kC$$

$$C_{out} = C_{in} \times e^{-k\theta}$$

$$\theta = \frac{V}{Q} = \frac{1.0 \times 10^6 \text{ gal}}{500 \text{ gal/min}} = 2 \times 10^3 \text{ min}$$

$$25 \text{ mg/L} = 100 \text{ mg/L} \times e^{-k(2 \times 10^3 \text{ min})}$$

$$k = 6.93 \times 10^{-4} / \text{min} \times 60 \text{ min/h} = \boxed{0.042 / \text{h}}$$

c)

$\theta = V/Q \rightarrow$ if θ doubles and Q remains constant, V must double.

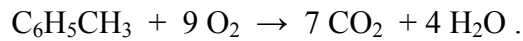
$$2 \times (1.0 \times 10^6 \text{ gal}) = \boxed{2 \times 10^6 \text{ gal.}}$$

8. (10 points) (Based on Mines & Lackey, page 58, Problem 3.10) An incinerator is being designed to burn toluene ($C_6H_5CH_3$, a type of volatile organic compound) from some fume flowing at 1,640 cubic feet per minute under ambient pressure and temperature of 250°F. The toluene concentration in the fume stream is 1,600 ppm on a volume basis, and the fume stream contains no oxygen.

Determine the minimum flow rate of air (in ft^3/min) entering at ambient pressure and at 60°F that needs to be fed to the combustion chamber to ensure complete thermal oxidation of the toluene.

If the allowed speed of incoming air is not to exceed 100 ft/s, determine the minimum cross-sectional area of the intake ducts.

Let us first write down the combustion equation for toluene. In the reaction, all the carbon C turns into carbon dioxide CO_2 and all the hydrogen H turns into water H_2O , thus after stoichiometric balance of the reaction equation, we have:



We then see that it takes 9 molecules of oxygen (O_2) to burn 1 molecule of toluene. Translated in moles, we find that it takes 9 moles of oxygen to burn 1 mole of toluene. To determine the amount of oxygen and, ultimately of air, necessary for the combustion, we need to determine how many moles of toluene are being fed on an ongoing basis to the incinerator.

For this we start with the entire flow rate of fumes of which we only take the toluene fraction:

$$V_{toluene} = 1,600 \text{ ppm of } 1,640 \frac{ft^3}{min} = (1,600 \times 10^{-6}) \left(\frac{1,640 \text{ } ft^3}{min} \right) = 2.624 \frac{ft^3}{min} .$$

In anticipation of the next step, we need to convert the volume into cubic meters. Thus,

$$V_{toluene} = \left(\frac{2.624 \text{ } ft^3}{min} \right) \left(\frac{0.3048 \text{ } m}{ft} \right)^3 = 0.07430 \frac{m^3}{min} .$$

Assimilating this portion to an ideal gas ($PV = nRT$) and knowing the pressure ($P = 1$ atm), the temperature ($250^\circ F = 121.11^\circ C \rightarrow T = 273.15 + 15.56 = 394.26$ K) and the volume per time ($V_{toluene} = m^3/min$), we can obtain the corresponding number of moles per time:

$$\begin{aligned} n &= \frac{PV}{RT} = \frac{(1 \text{ atm})(0.07430 \text{ } m^3 / \text{min})}{(8.206 \times 10^{-5} \text{ } atm \cdot m^3 / \text{moles} \cdot K)(394.26 \text{ } K)} \\ &= 2.297 \frac{\text{moles}}{\text{min}} . \end{aligned}$$

The necessary number of moles of oxygen is nine times this amount:

$$\begin{aligned} n_{O_2} &= 9 \frac{\text{moles of } O_2}{\text{moles of toluene}} \times 2.297 \frac{\text{moles of toluene}}{\text{min}} \\ &= 20.67 \frac{\text{moles of } O_2}{\text{min}} \end{aligned}$$

from which the number of moles of air follows since oxygen is 20% of air:

$$\begin{aligned} n_{air} &= \frac{1 \text{ mole of air}}{0.20 \text{ moles of } O_2} \times \frac{20.67 \text{ moles of } O_2}{\text{min}} \\ &= 103.35 \frac{\text{moles of air}}{\text{min}}. \end{aligned}$$

Assimilating the air to an ideal gas, we can determine the volumetric flow rate corresponding to this rate of moles and at the intake temperature ($60^\circ\text{F} = 15.56^\circ\text{C} \rightarrow T = 273.15 + 15.56 = 288.71 \text{ K}$):

$$\begin{aligned} V_{air} &= \frac{nRT}{P} = \frac{(103.35 \text{ moles / min})(8.206 \times 10^{-5})(288.71 \text{ K})}{(1 \text{ atm})} \\ &= 2.448 \frac{m^3}{\text{min}}. \end{aligned}$$

Converting this into the desired units, we obtain:

$$Q_{air} = \left(\frac{3.344 \text{ m}^3}{\text{min}} \right) \left(\frac{1 \text{ ft}}{0.3048 \text{ m}} \right)^3 = 86.47 \frac{\text{ft}^3}{\text{min}}.$$

The minimum cross-sectional area of the duct is

$$A_{\min} = \frac{Q_{air}}{u_{\max}} = \frac{(86.47 \text{ ft}^3 / \text{min})}{(100 \text{ ft} / \text{s})(60 \text{ s} / \text{min})} = 0.0144 \text{ ft}^2.$$