Solutions for Assignment - 5

Important point:
Solutions can be different according to the individual assumptions

1. A trash incinerator has an effective stack height of 100 m. On a sunny day with a 2 m/s wind the concentration of sulfur dioxide 200 m directly downwind is measured at 5.0×10^{-5} g/m^3. Estimate the mass release rate (in g/s) of sulfur dioxide from this stack. Also estimate the maximum sulfur dioxide concentration expected on the ground and its location downwind from the stack.

Solution:

This is a continuous release. For a sunny day a wind stability class A with wind velocity 2 m/s can be assumed. The ground concentration directly downwind for that condition is given by

$$C(x,0,0) = \frac{Q}{\Pi \sigma_z \sigma_y U} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]$$

In a rural area for the stability class A the dispersion coefficients are obtained from Table-2 at page .

$$\sigma_y = 0.22\ X(1+0.0001X)^{-0.5}$$
$$= 0.22 \times 200 \times (1+0.0001 \times 200)^{-0.5} = 43.56\ \text{m}$$

$$\sigma_z = 0.20\ X$$
$$= 0.20 \times 200 = 40\ \text{m}$$

From the equation we obtain:

$$5 \times 10^{-5}\ \frac{g}{m^3} = \frac{Q_m}{3.14 \times 43.56\ \text{m} \times 40\ \text{m} \times 2\frac{\text{m}}{\text{s}}} \exp\left[-\frac{1}{2}\left(\frac{100\ \text{m}}{40\ \text{m}}\right)^2\right]$$

$$Q_m = 12.43\ \text{g/s}$$

The location of the maximum concentration is found by:

$$\sigma_z = \frac{H}{\sqrt{2}} = \frac{100\ \text{m}}{\sqrt{2}} \approx 70\ \text{m}$$

Now, the distance x is obtained from:

$$0.2X = 70\ \text{m}$$

$$X = 350\ \text{m}$$

New dispersion coefficients are:

$$\sigma_y = 0.22\ X(1+0.0001X)^{-0.5}$$

$$= 0.22 \times 350 \times (1+0.0001\times 350)^{-0.5} = 75.68\ \text{m}$$

$$\sigma_z = 70\ \text{m}$$

The expected max.sulfur dioxide concentration on the ground is estimated by:

$$C(\max) = \frac{2Q_m}{\Pi U H^2} \exp\left[\left(\frac{\sigma_z}{\sigma_y}\right)\right]$$

$$= \frac{2\times 12.43\frac{g}{s}}{3.14\times 2\frac{m}{s}\times (100\ \text{m})^2} \exp\left[\left(\frac{70\ \text{m}}{75.68\ \text{m}}\right)\right]$$

$$= \frac{24.86}{6.28\times 10^4}\times 2.52\ \text{g/m}^3 = 9.96\times 10^{-4}\ \text{g/m}^3$$

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2. A reactor in a pesticide plant contains 1000 lb of a liquid mixture of 50% by weight liquid methyl isocyanate (MIC). The liquid is near its boiling point. A study of various release scenarios indicates that a rupture of the reactor will spill the liquid into a boiling pool on the ground. The boiling rate of MIC has been estimated to be 20 lb/min. Evacuation of the population must occur in areas where the vapor concentration exceeds ERPG-1 (5 *ppm* or 12.5 mg/m^3). If the wind speed is 3.4 mph on a clear night, estimate the area downwind that must be evacuated.

Solution:

A plume of MIC can form during evaporation of MIC from the boiling pool. From the Table-1, for the wind speed is 3.4 mph or 1.52 m/s and a clear night condition the stability class is F. Using Table-2, in a rural area for stability class F, the dispersion coefficients are given by:

$$\sigma_y = 0.04\ X(1+0.0001X)^{-0.5} \qquad [1]$$

$$\sigma_z = 0.016\ X(1+0.0003X)^{-1.0} \qquad [2]$$

Let X is the location of the maximum concentration. The maximum concentration on ground with release height H=0 is given by:

$$C(x,0,0) = \frac{Q}{\Pi \sigma_z \sigma_y U}$$

Here,

Q_m = 20 lb/min =151.2 g/s

Maximum acceptable concentration C = 5 *ppm* or 12.5 mg/m^3 or 0.0125 g/m^3

Now,

$$0.0125 \frac{g}{m^3} = \frac{151.2 \frac{g}{s}}{3.14 \times \sigma_z \sigma_y \times 1.52 \frac{m}{s}}$$

$$\sigma_z \sigma_y = 2534 \qquad [3]$$

Using Maple to solve the equations for X, we have,

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> solve( {Sy-0.04*X*(1+0.0001*X)^(-0.5)= 0, Sz-
0.016*X*(1+0.0003*X)^(-1.0)= 0, Sy*Sz-2534=0}, [Sy,Sz,X]);
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$$Sy = 102.1274775, Sz = 24.81212758, X = 2899.845562$$

Therefore, the downwind distance X is 2899.845 ≈ 2900 m or 2.9 km. The evacuated area is given by:

$$A = \frac{\pi \times X^2}{4}$$

$$= \frac{\pi \times (2.9\ \text{km})^2}{4} = 6.60\ \text{km}^2$$

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3. The EPA Risk Management Plan (RMP) defines a worst-case scenario as the catastrophic release of the entire process inventory in a 10-min period (assumed to be a continuous release). The dispersion calculations must be completed assuming F stability and 1.5 m/s wind speed. As part of the RMP rule, each facility must determine the downwind distance to a toxic endpoint. These results must be reported to the EPA and to the surrounding community.
    a. A plant has a 100-lb tank of anhydrous hydrogen fluoride (molecular weight = 20). The toxic endpoint is specified in the RMP as 0.016 mg/L. Determine the distance downwind (in miles) to the toxic endpoint for an EPA worst-case release.

b. Comment on the viability of using a continuous release model for a 10-min release period.

c. One hundred pounds of HF is a small quantity. Many plants have much larger vessels on site. Comment on how a larger quantity would affect the downwind distance and how this might affect the public's perception of your facility.

Solution:

a. Downwind distance Determination

Given, a continuous release, stability class F and wind speed 1.5 m/s.

The specified RMP toxic endpoint is 0.016 mg/L or 0.016 g/m^3

The release rate is: $Q_m = \dfrac{100 \text{ lb}}{10 \text{ min}} = \dfrac{453.6 \text{ g}}{10 \times 60 \text{ s}} = 75.6 \, g/s$

Using Table-2, in a rural area for stability class F, the dispersion coefficients are given by:

$$\sigma_y = 0.04\,X(1 + 0.0001X)^{-0.5} \qquad [1]$$

$$\sigma_z = 0.016\,X(1 + 0.0003X)^{-1.0} \qquad [2]$$

The maximum concentration will occur at the centerline. So, we have

$$C(x,0,0) = \frac{Q_m}{\Pi \sigma_z \sigma_y U}$$

$$0.016 \frac{g}{m^3} = \frac{75.6 \frac{g}{s}}{3.14 \times \sigma_z \sigma_y \times 1.5 \frac{m}{s}}$$

$$\sigma_z \sigma_y = 1003.18 \qquad [3]$$

Using Maple to solve the equations for X, we have,

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> solve( {Sy-0.04*X*(1+0.0001*X)^(-0.5)= 0, Sz-0.016*X*(1+0.0003*X)^(-1.0)= 0,
Sy*Sz-1003.18=0}, [Sy,Sz,X]);
[Sy = 58.59255562, Sz = 17.12128767, X = 1576.021400]
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Therefore, the downwind distance X is 1576 m or 1.6 km ≈ 1 mile.

b. Viability checking:

$$F = \left(\frac{uR_d}{x}\right) = \frac{1.5 \times 10 \times 60}{1576} = 0.57 \leq 0.6$$

Since F <0.6, instantaneous model may be a better choice in order to get more conservative estimation.

c. The downwind distance will be increased with the increase of HF quantity. Then more area needs to be evacuated to avoid the exposure with toxic HF.

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4. The emergency coordinator has decided that the appropriate emergency response tot eh immediate release of a toxic material is to alert people to stay in their homes, with doors and windows closed, until the cloud has passed. The coordinator has also indicated that homes 4000 m downwind must not be exposed to concentrations exceeding 0.10 mg/m^3 of this material for any longer than 2 min. Estimate the maximum instantaneous release of material (in kg) allowed for these specifications. Be sure to clearly state any assumptions about weather conditions, wind speed, etc.

<u>Solution:</u>

For instantaneous release of material, the maximum concentration occurs at the center of the cloud directly downwind from the release.

$$C(ut,0,0,t) = \frac{Q_{inst}}{\sqrt{2}\Pi^{3/2}\sigma_x\sigma_y\sigma_z}$$

The stability classes are selected to maximize the release of material in the above equation. This requires maximum value of dispersion coefficients which occurs with A stability conditions. This is for daytime conditions with strong solar radiation and a surface wind speed less than 2 m/s. Therefore at 4000m downwind from Table-3 we have the dispersion coefficients are:

$$\sigma_x \text{ or } \sigma_y = 0.18\ X^{0.92} \quad = 370.82 \text{ m}$$

$$\sigma_z = 0.60\ X^{0.75} \quad = 301.78 \text{ m}$$

Now, maximum instantaneous release of material (in kg) is obtained by:

$$0.10\times10^{-3}\,\frac{g}{m^3}=\frac{Q_{inst}}{\sqrt{2}\times(3.14)^{3/2}\times372.82\ m\times372.82\ m\times301.78\ m}$$

$$Q_{inst}=32653\ g=32.65\ kg$$

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5. A tank of Chlorine contains 1000 kg of Chlorine at 50 bar gauge (1 bar =10^5 Pa). What is the maximum hole diameter in this tank that will result in a downwind concentration equal to the ERPG -1 (1 ppm) at a downwind distance of 300 m. You may consider molecular weight of Chlorine as 71 at 1 atm pressure and 298 K and all liquid chlorine vaporize (vapor release model).

Solution:

Through the hole of the tank, a plume of Chlorine vapor is assumed to be dispersed at a downwind distance of 300 m. The largest plume will occur when the dispersion coefficients are smallest and wind speed is small. This usually occurs with stability class F and a rural release.

Therefore, a stability class F with wind speed 2 m/s in a rural seating is considered.

The maximum concentration on ground with release height H=0 is given by:

$$C(x,0,0)=\frac{Q}{\Pi\sigma_z\sigma_y U}$$

From Table -2: for the stability class F the dispersion coefficients are obtained by:

$$\sigma_y=0.04\ X(1+0.0001X)^{-0.5}$$
$$=0.04\times300\times(1+0.0001\times300)^{-0.5}=11.82\ m$$

$$\sigma_y=0.016\ X(1+0.0003X)^{-1.0}$$
$$=0.016\times300\times(1+0.0003\times300)^{-1.0}=4.40\ m$$

The downwind concentration in g/m^3 is given by

$$C_{ppm}=0.08205\times\frac{T}{PM}\times\frac{mg}{m^3}$$

$$C\ \text{in mg/m}^3=\frac{1\times1\times71}{298\times0.08205}=2.9\ mg/m^3=2.9\times10^{-3}\,g/m^3$$

Now,

$$2.9\times10^{-3}\ \frac{g}{m^3}=\frac{Q_m}{3.14\times11.82\ m\times4.40\ m\times2\frac{m}{s}}$$

$$Q_m=0.95\ \frac{g}{s}=0.95\times10^{-3}\ \frac{kg}{s}$$

Since the storage pressure is 50 bars which is greater than then the atmospheric pressure a choked released will be occurred during chlorine vapour release from the tank.

For choked flow, the release rate is calculated by:

$$Q_{m(chocked)}=C_oAP_o\sqrt{\frac{\gamma g_c M}{R_g T_o}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

Here,

P_0 is upstream pressure, = 50 bar = 5 × 10^6 N/ m^2

M is molecular weight of chlorine = 0.071 g/g-mole

R is gas constant, 8.314 × 10^3 N- m^3/Kg-mole-K- s^2

T_0 is gas temperature, K=298 K

A discharge area, = ?

γ, Specific heat ratio; for chlorine =1.3

C_0 is Gas discharge coefficient = 1 [assumed]

g_c is 1 kg-m/N- s^2

Q_m minimum release rate from part a = 0.95 g/s

Therefore the area, A is required to produce release rate 37.2 kg/s is given by:

$$0.95\times10^{-3}\ \frac{kg}{s}=1\times A\times5\times10^6\ \frac{N}{m^2}\times\sqrt{\frac{1.3\times1\frac{kg-m}{N-s^2}\times71\frac{kg}{kg-mole}}{8.314\times10^3\ \frac{N-m^3}{kg-k-s^2}\times298\ K}\left(\frac{2}{1.3+1}\right)^{\frac{1.3+1}{1.3-1}}}$$

$$0.95\times10^{-3}=1\times A\times5\times10^6\times3.60\times10^{-3}$$

$$A=5.3\times10^{-8}\ m^2$$

Maximum hole diameter in the tank:

$$A = \frac{\pi \times d^2}{4}$$

$$d = \sqrt{\frac{5.3 \times 10^{-8} \times 4}{3.14} m^2} = 2.6 \times 10^{-4}.\ m = 0.026.\ cm$$

Table-1: Atmosphere stability

Surface wind speed	Day, incoming solar radiation			Night, Cloud cover thickly overcast		Anytime Heavy overcast
	Strong	Moderate	Slight	>1/2 Low clouds	<3/8 clouds	
<2 m/s	*A	A-B	B	F	F	D
2-3 m/s	A-B	B	C	E	F	D
3-5 m/s	B	B-C	D	D	E	D
5-6 m/s	C	C-D	D	D	D	D
> 6 m/s	C	D	D	D	D	D

Table-2:Dispersion co-efficient for plume model

Area	Stability Class	σ_y (m)	σ_z (m)
Rural conditions	A	$0.22X\,(1+0.0001X)^{-0.5}$	$0.20X$
	B	$0.16X\,(1+0.0001X)^{-0.5}$	$0.12X$
	C	$0.11X\,(1+0.0001X)^{-0.5}$	$0.08X\,(1+0.0002X)^{-0.5}$
	D	$0.08X\,(1+0.0001X)^{-0.5}$	$0.06X\,(1+0.0015X)^{-0.5}$
	E	$0.06X\,(1+0.0001X)^{-0.5}$	$0.03X\,(1+0.0003X)^{-1.0}$
	F	$0.04X\,(1+0.0001X)^{-0.5}$	$0.016X\,(1+0.0003X)^{-1.0}$
Urban conditions	A-B	$0.32X\,(1+0.0004X)^{-0.5}$	$0.24X\,(1+0.0001X)^{0.5}$
	C	$0.22X\,(1+0.0004X)^{-0.5}$	$0.20X$
	D	$0.16X\,(1+0.0004X)^{-0.5}$	$0.14X\,(1+0.0003X)^{-0.5}$
	E-F	$0.11X\,(1+0.0004X)^{-0.5}$	$0.08X\,(1+0.0015X)^{-0.5}$

Table-3: Dispersion co-efficient for puff model

Area	Stability Class	σ_x or σ_y (m)	σ_z (m)
Rural conditions	A	$0.18X^{0.92}$	$0.60X^{0.75}$
	B	$0.14X^{0.92}$	$0.53X^{0.73}$
	C	$0.10X^{0.92}$	$0.34X^{0.71}$
	D	$0.06X^{0.92}$	$0.15X^{0.70}$
	E	$0.04X^{0.92}$	$0.10X^{0.65}$
	F	$0.02X^{0.89}$	$0.05X^{0.61}$

(Ref: Crowl D.A., Louvar J.F. (2002). ”Chemical Process Safety, Fundamentals with Applications)