B.Sc. Course(Second Semester)

University of Babylon-College of Engineering

Environmental Engineering Department

<u>Hazardous Waste Incineration (HWI)</u>

HWI.1 Destruction And Removal Efficiency(DRE):

By federal law, hazardous waste incinerators must meet a minimum destruction and removal requirement, i.e., that the principal organic hazardous constituents (POHCs) of the waste feed be incinerated with a minimum destruction and removal efficiency(DRE) of 99.99% ("four nines"). The destruction and removal efficiency is the fraction of the inlet mass flow rate of a particular chemical that is destroyed and removed in the incinerator or, equivalently,

$$DRE = 1 - \frac{Mass\ flow\ of\ chemical\ out}{Mass\ flow\ of\ chemical\ in}$$

A feed stream to a rotary kiln incinerator contains 245 kg/h of solid waste. Calculate the maximum outlet flow rate of solid waste from the incinerator allowed by law.

Solution:

Substituting data given in the problem statement into the DRE equation provides the means of determining an acceptable mass flow rate of chemical out of the incinerator as follows:

$$DRE = 1 - \frac{Mass\ flow\ of\ chemical\ out}{Mass\ flow\ of\ chemical\ in}$$

$$0.9999 = 1 - \frac{Mass\ flow\ of\ chemical\ out}{245\ kg/h}$$

$$Mass\ flow\ of\ chemical\ out = (1 - 0.9999)(245\ kg/h) = (0.0001)(245\ kg/h)$$

$$= 0.0245\ kg/h$$

HWI.2 Regulation Of Particulate Emissions:

Some state regulations limit stack emissions of particulate material from a hazardous waste incinerator to an outlet loading of 0.08 gr/dscf (grains of particulate per dry standard cubic foot of stack gas), corrected to 7% oxygen (or an approximate excess air level of 50%).

1. Describe the effect on the outlet particulate loading of each of the three following actions as far as increasing or decreasing the measured value of the outlet loading. Give a reason for each answer.

a. Removing water from the gas (Note: The incineration of organic material almost always produces water as a product.)
b. Lowering the temperature of the gas from its stack temperature of 800°F to the standard temperature of 60°F.
c. Using 50% excess air for the incineration instead of 100% excess air.

2. From the three answers provided to part 1, explain why the terms "dry," "standard," and "corrected to 7% oxygen" are used in the regulations.

Solution:

1. Removing water from the gas decreases the gas volume without affecting the mass of particulate matter. Since the particulate loading is the mass of particulate matter divided by the gas volume, the particulate loading increases.

Lowering the temperature also decreases the gas volume without affecting the particulate mass. Therefore, the loading increases. The less excess air used for the combustion, the less oxygen and nitrogen contribute to the gas stream. The gas volume is therefore lower and the particulate loading increases.

2. "Dry" is used so that extra water cannot be added to the gas stream to artificially lower the outlet particulate loading. "Standard" is used so that the outlet particulate loading is not a function of temperature, i.e., the loading cannot be artificially lowered by raising the temperature. "Converted to 7% oxygen" is used so that the outlet particulate loading cannot be artificially lowered by using an inordinate amount of excess air.

HWI.3 Incinerator Output Loading:

An incinerator is burning a hazardous waste slurry using 50% excess air. The stack gas at 800°F has a flowrate of 10000 acfm (actual cubic feet per minute) with a particulate mass flow of 20 gr/min and a water content of 10% by volume. The maximum allowed outlet loading for particulates is 0.08 gr/dscf (grains per dry standard cubic foot), corrected to 7% oxygen (or an approximate excess air level of 50%).

1. Calculate the outlet loading in gr/acf (grains per actual cubic foot).
2. Calculate the outlet loading in gr/scf (grain per standard cubic foot) noting that standard temperature is 60°F.
3. Calculate the outlet loading in gr/dscf.
4. As far as particulates are concerned, is the incinerator in compliance?

Solution:

1. The outlet loading (OL) in gr/acf is given by:

$$OL_{gr/acf} = \frac{150\ gr/min}{10000\ ft^3/min} = 0.015\ gr/acf$$

2. From the ideal gas law (Harles law), the volume is proportional to the absolute temperature. Noting that T(°R)=T(°F)+460, the outlet loading in gr/scf is

$$OL_{gr/scf} = (0.015\ gr/ft^3)\left(\frac{800 + 460^0R}{60 + 460^0R}\right) = 0.036\ gr/scf$$

3. Since the gas stream is 10% water by volume, the outlet loading in gr/dscf is given by:

$$OL_{gr/dscf} = (0.036\ gr/ft^3)\left(\frac{100\ ft^3_{wet}}{90\ ft^3_{dry}}\right) = 0.0403\ gr/dscf$$

4. Because 50% excess air (approximately 7% O_2) is used, the outlet loading is 0.0403 gr/dscf corrected to 7% O_2. This is below the allowed maximum particulate concentration of 0.08. therefore, The incinerator is in compliance.

HWI.4 Determination Of Compliance For Particulate Emissions:

A hazardous waste incinerator is burning an aqueous slurry of soot(i.e., carbon) with the production of a small amount of fly ash. The waste is 70% water by mass and is burned with 0% excess air (EA). The flue gas generated contains 0.30gr of particulates in each 8.0 ft^3 (actual) at 580°F.

If the state regulations require the particulate emissions by less than 0.08 gr/dscf corrected to 50% EA, is this incinerator in compliance or must additional particulate control measures be taken? Assume that when the flue gas passes through a waste heat boiler no water condensation occurs.

Solution:

The particulate concentration in the flue gas is

$0.30\ gr\ /8.0\ acf = 0.0375\ gr/acf$

Using Charles law, one can calculate the volume at 60°F =520°R:

$(8.0\ acf)(520^0R/1040^0R) = 4.0\ scf$

$Particulate\ concentration = 0.30\ gr/4.0\ scf = 0.075\ \ gr/scf$

The volume fraction of water in the flue gas is obtained from the mass composition of the waste and the balanced equation:

$C + H_2O + O_2 \rightarrow CO_2 + H_2O$

For each 100Ib of waste (30Ib C and 70Ib water), the following molar quantities are input to the incinerator

$C{:}\ 30Ib/(12\ Ib/Ibmol) = 2.5\ Ibmol$

$Water{:}\ 70Ib/(18\ Ib/Ibmol) = 3.89\ Ibmol$

$Oxygen{:}\ 2.5\ Ibmol$

$Nitrogen{:}\ (79/21)(2.5\ Ibmol) = 9.40\ Ibmol$

Fraction of water in flue gas y_{FC} , is

$$y_{FG} = \frac{3.89}{2.5 + 3.89 + 9.4} = 0.25$$

The molar quantity of dry gas , n_{DG} is

$n_{DG} = (2.5 + 9.4) = 11.9\ Ibmol$

The dry volume is calculated by subtracting the volume of water from the total gas volume shown as:

$(4.0\ scf)(1 - 0.25) = 3.0\ dscf$

The particulate concentration on a dscf basis is then calculated as:

$Particulate\ concentration = 0.30\ gr/3.0\ dscf = 0.10\ gr/scf$

To correct to 50% EA, 50% more N_2 and O_2 are added to the flue gas:

$Excess\ nitrogen\ added = 0.5(79/21)(2.5Ibmol\ ) = 4.7Ibmol$

$Excess\ oxygen\ added = 0.5(2.5) = 1.25\ Ibmol$

The total moles of dry flue gas is increased by the EA to yield a total of

$2.5 + 9.4 + 4.7 + 1.25 = 17.85\ Ibmol$

The total flue gas volume can then be calculated based on the ratio of total moles of flue gas at 50% and at 0% EA.

$3.0\ dscf(17.85\ Ibmol/11.89\ Ibmol) = 4.5\ dscf\ \ (50\%\ EA)$

The particulate concentration on a dry weight basis, corrected to 50% EA is:

$0.30\ gr/4.5\ dscf\ (50\%\ EA) = 0.067\ \ gr/dscf\ \ (50\%\ EA)$

Since this does not exceed the state particulate standard, the incinerator is in compliance. The reader should note that particulate standard most often employed today is in the 0.015-0.03 gr/dscf (corrected to 50% EA) range.

HWI.5 Control Of HCI And Particulates:

A state incinerator emissions limit requires 99% HCl control and allows 0.07 gr/dscf at 68°F, corrected to 50% EA. An incinerator is to burn 5 tons/h hazardous sludge waste containing 2% Cl, 80% C, 5% inerts, and the balance H_2O by weight. Perform the following calculations:

1. Calculate the maximum mass emission rate equivalent HCl in Ib/h that may be emitted.
2. Calculate the maximum mass emission rate of particulates in Ib/h that may be emitted. What is the actual particulate emission rate if all the inerts are emitted from the stack as fly ash?
3. Determine the combustion efficiency of this incinerator if a stack test indicates that the flue gas contains 12% CO_2 and 20ppm CO.

Solution:

The incinerator receives 5 tons/h of waste with 2% Cl content. Assuming all chlorine is converted to HCl, the amount of HCl formed is given as:

$$Cl\ in\ feed = (5\ \ ton/h)(2000\ \ Ib/ton)(0.02\ \ Ib\ Cl/Ib\ waste) = 200\ \ Ib\ Cl/h$$

$$HCl\ \ formed = [(200\ \ Ib\ Cl/h)(36.5\ Ib\ HCl)]/(35.5\ Ib\ Cl) = 205.6\ \ Ib\ HCl/h$$

The maximum permissible mass emission rate of HCl at 99% control is

$$(205.6\ \ Ib\ HCl/h)(1 - 0.99) = 2.06\ \ Ib\ HCl/h\ emitted$$

To calculate particulate emissions at 50% EA, a 1-mole C basis is used along with the following balanced equation:

$$C + 1.5\ O_2 + 1.5(79/21)\ N_2 = CO_2 + 0.5\ O_2 + 1.5(79/21)\ N_2$$

The volume of flue gas generated per Ibmol of C combusted is calculated from the ideal gas law:

$$V = \frac{nRT}{P} = \frac{[1 + 0.5 + 1.5(3.76)]Ibmol(460 + 68)°R[0.7302\ \ atm.ft^3/(Ibmol.°R)]}{1\ atm}$$

$$= 2754\ dscf$$

Based on the required incinerator emission standard of 0.07 gr/dscf, the maximum emission rate allowed at 50% EA is as follows. The volume of gas generated per hour, q, can be calculated:

$$q = \left(5\frac{ton\ fuel}{h}\right)\left(2000\frac{Ib\ fuel}{ton\ fuel}\right)\left(0.8\frac{Ib\ C}{Ib\ fuel}\right)\left(\frac{1\ Ibmol\ C}{12\ Ib\ C}\right)\left(\frac{2754\ \ dscf\ flue\ gas}{Ibmol\ C}\right)$$
$$= 1836000\ \ dscf/h$$

The allowable particulates discharge rate is

$$\dot{m}_{allowed} = (1836000\ \ dscf/h)(0.07\ \ gr\ particulates/dscf)(1\ Ib/7000\ gr)$$
$$= 18.36\ \ Ib\ particulates/h$$

The actual particulates emission rate is

$$\dot{m}_{actual} = (5\ \ ton\ fuel/h)(2000\ \ Ib/ton)(0.05\ Ib\ ash/Ib\ fuel) = 500\ \ Ib\ particulates/h$$

This is well above the allowable limit, requiring particulate removal to meet permit requirements.

The actual combustion efficiency can be calculated based on the ratio of carbon dioxide to total effluent carbon species in the flue gas effluent, and is

$$Combustion\ efficiency = \left(\frac{CO_2}{CO_2 + CO}\right) = \left(\frac{12}{12 + 0.0020}\right)(100) = 99.98\%$$

HWI.6 Theoretical Flame Temperature Estimation:

Estimate the theoretical flame temperature of a waste mixture containing 25% cellulose, 35% motor oil, 15% water (vapor), and 25% inerts, by mass. Assume 5% radiant heat losses. The flue gas contains 11.8% CO_2, 13% CO, and 10.4% O_2 (dry basis) by volume.

NHV of cellulose=14000 Btu/Ib

NHV of motor oil=25000 Btu/Ib

NHV of water=0 Btu/Ib

NHV of inerts (effective)=-1000 Btu/Ib

Assume the average heat capacity of the flue gas is 0.325 Btu/(Ib.°F). Employ the Theodore-Reynolds equation to perform this calculation:

$$T = 60 + \frac{NHV}{0.325[1 + (1 + EA)(7.5 \times 10^{-4})(NHV)]}$$

Solution:

Determine the net heating value (NHV) for the mixture:

$$NHV = 0.25(14000\ Btu/Ib) + 0.35(25000\ Btu/Ib) + 0.15(0.0\ Btu/Ib) + 0.25(-1000\ Btu/Ib) = 12000\ Btu/Ib$$

Determine the excess air employed. If Y is the % by volume of O_2 (dry basis),then

$$EA = 0.95Y/(21 - Y) = 0.95(10.4)/(21 - 10.4) = 0.932$$

Estimate the flame temperature using the Theodore-Reynolds equation.

$$T = 60 + \frac{NHV}{0.325[1 + (1 + EA)(7.5 \times 10^{-4})(NHV)]}$$

$$T = 60 + \frac{12000}{0.325[1 + (1 + 0.932)(7.5 \times 10^{-4})(12000)]} = 2068°F$$

HWI.7 Effect Of PCB Concentration On Combustion:

Polychlorinated biphenyls (PCBs) are mixed with some solids and waste oil for burning in a rotary kiln incinerator. What will happen as the percentage of PCBs is increased in the waste mixture assuming that all other variables (i.e., excess air, heat loss, feed rate) are kept constant?

Solution:

As the percentage of PCB increases in the waste mixture, the following will occur:

1. Incinerator temperature will decrease because of the low heat of combustion of PCBs.
2. The efficiency of combustion will decrease because as the combustion temperature decreases the PCBs are more difficult to incinerate at a lower temperature.
3. The concentration of Cl_2 in the flue gas will increase; at lower temperatures, the $HCl \leftrightarrow Cl_2$ equilibrium is shifted toward Cl_2.

HWI.8 Residence Time:

One incinerator at a hazardous waste facility operates at 2200°F with a combustion gas flowrate of 40000 acfm. If the incinerator is 10 ft wide, 12 ft deep, and 22 ft high, calculate the maximum residence time in the incinerator. The combustion gas flowrate through a second incinerator at the facility, which is operating at 2000°F, is 5000 scfm(60°F). If the incinerator requires a minimum residence time of 2s, calculate the required volume of this incinerator.

Solution:

Calculate the volume, V, of the first incinerator:

$V = (width)(length)(depth) = (10)(12)(22) = 2640\ ft^3$

Calculate the maximum residence time, θ:

$\theta = V/q_a = (2460/40000)(60) = 3.96s$

Calculate the actual combustion gas flowrate for the second incinerator:

$q_a = q_s(T_a/T_s) = (5000)(2000 + 460)/(60 + 460) = 23650\ acfm$

The volume required is therefore

$V = q_a\theta = (23650)(2)/60 = 788\ ft^3$

Note that the residence time is a function of the temperature since the volumetric flowrate is linearly related to the absolute temperature. Thus , the higher the operating temperature the shorter the residence time. In addition, the gas residence time calculated above by dividing the volume of the incinerator chamber by the combustion gas flowrate is an approximate value. This does not include flowrate variations that arise due to chemical reaction and temperature changes through the unit. Thus, a residence time distribution exists with real systems.

HWI.9 pH Control:

Process considerations require pH control in a 50000-gal storage tank used for incoming waste mixtures (including liquid plus solids) at a hazardous waste incinerator. Normally, the tank is kept at neutral pH. However, operation can tolerate pH variations from 6 to 8. Waste arrives in 5000-gal shipments. Assume that the tank is completely mixed, contains 45000gal when the shipment arrives, the incoming acidic waste is fully dissociated, and that there is negligible buffering capacity in the tank.

1. What is the pH of the most acidic waste shipment that can be handled without neutralization?
2. What is the pH of the most acidic waste shipment that can be handled without neutralization if the storage tank volume is 100000gal, and contained 95000gal of neutral waste when the shipment arrived?

Solution:

1. The pH of the most acidic waste shipment that can be handled without neutralization is calculated as follows: 5000gal of waste with a $[H^+]$=X is diluted by 45000gal at pH=7 or$[H^+]=10^{-7}$. The minimum pH of 6 that can be tolerated is equivalent to a $[H^+]=10^{-6}$. From an ion balance:

$[H^+] = 10^{-6} = (5000/50000)X + (45000/50000)(10^{-7})$

$$X = \left(\frac{50000}{5000}\right)\left[10^{-6} - \frac{45000(10^{-7})}{5000}\right] = 0.91 \times 10^{-6}$$

$pH = 6.04$

2. With a tank volume of 100000gal, the solution is as follows:

$10^{-6} = (5000/100000)X + (95000/100000)(10^{-7})$

$$X = \left(\frac{100000}{5000}\right)\left[10^{-6} - \frac{95000(10^{-7})}{100000}\right] = 1.81 \times 10^{-5}$$

$pH = 4.74$

HWI.10 Dre And NHV Calculation:

A mixture of trichloroethylene, tetrachlorethylene, dichlorofluoromethane, and phthaloyl chloride in No. 2 fuel oil (1% sulfur) is fired during a trial burn in a liquid injection incinerator. The facility is equipped with a quench tower, venture scrubber, and packed-bed caustic scrubber.

Each of the four organic compounds makes up 5% (by weight) of the waste /fuel feed of 5000 Ib/h. The excess air is 35%. The stack gas flowrate, corrected to 7% oxygen and standard conditions (1 atm, 25°), is 21300 dscfm.

1. Calculate the destruction and removal efficiency (DRE) for each hazardous constituent using the flue gas measurements below:

C_2HCl_3	0.03 ppm
C_2Cl_4	0.02 ppm
$CHCl_2F$	0.30 ppm
$C_3H_4Cl_2O$	1.8 ppm

2. Use Dulongs equation to calculate the NHV of the mixture in Btu/Ib. The NHV of No.2 fuel oil is 18650 Btu/Ib.

Solution:

1. As described earlier, the DRE for each hazardous material is related to its mass flowrate into, $\dot{m}_i$, the HWI and the mass flowrate out of , $\dot{m}_0$, the stack by the equation:

$$DRE = \left(1 - \frac{\dot{m}_0}{\dot{m}_i}\right)100$$

Where , $\dot{m}_0$ is equal to the product of the mass concentration in the stack, ρ_0 , and the volumetric flowrate, c_0, out the stack. Each stack gas concentration, c_0, in ppm can be shown to be converted to ρ_0 by the following equation at $25°C$ and 1 atm pressure:

$\rho_0 = 40.9\, c_0(MW)$

Where ρ_0 is in $\mu g/m^3$ and MW is the gram molecular weight.

The inlet mass of each compound is 5% of the inlet waste feed $= 0.05(5000\ Ib/h) = 250\ Ib/h$

With the above information the table below was constructed.

	$\dot{m}_i$ (lb/h)	MW	c_o (ppm)	ρ_o (g/m^3)	$\dot{m}_o$ (lb/min)	DRE (%)
C_2HCl_3	250	131.5	0.03	161.35	2.147×10^{-4}	99.9999
C_2Cl_4	250	166	0.02	135.79	1.807×10^{-4}	99.9999
$CHCl_2F$	250	103	0.30	1263.8	1.682×10^{-3}	99.9993
$C_3H_4Cl_2O$	250	187	1.8	13,766.9	1.83×10^{-2}	99.9927

2. Assume F and Cl have essentially the same influence on the waste NHV. The calculation of the mass fraction of each element in each waste compounds is illustrated (for carbon in C_2HCl_3) below:

$$Mass\ fraction\ C = \left(\frac{(2)(12)}{131.5}\right) = 0.1825$$

$\dot{m}_C = (0.1825)(250) = 45.6\ Ib/h$

The remaining values in the table are calculated in an identical manner.

	$\dot{m}_i$ (lb/h)	MW	$\dot{m}_C$	$\dot{m}_H$	$\dot{m}_{Cl}$ (&) $\dot{m}_F$	$\dot{m}_O$
C_2HCl_3	250	131.5	45.6	1.9	202.5	
C_2Cl_4	250	166	36.1		213.9	
$CHCl_2F$	250	103	29.13	2.43	218.45	
$C_3H_4Cl_2O$	250	187	48.1	5.35	94.92	21.4
Total	1000		158.9	9.68	729.77	21.4

In this table, a basis of 1000 Ib/h total waste flow of the four compounds was used. The NHV can be calculated for this four-compound mixture using Dulongs equation:

$NHV = 14000\, x_C + 45000[x_H - (x_0/8)] - 760 x_{Cl} + 4500 x_S$

Where x_i=mass fraction of i.

The mass fractions are calculated by dividing the $\dot{m}_i$ for each element by 1000 Ib/h.

$$NHV = 14000(0.159) + 45000[0.00968 - (0.0214/8)] - 760(0.7298) + 0$$

$$= 1987 \ Btu/Ib$$

The NHV of the entire waste mixture, i.e., the 4 compounds and the No.2 fuel oil, can be calculated as follows:

$$NHV_{mixture} = 0.8(18650 \ Btu/Ib \ fuel \ oil) + 0.2(1987 \ Btu/Ib \ waste \ compounds)$$

$$= 15320 \ Btu/Ib$$