Environment Institute of Malaysia (E*i*MAS)
Department of Environment

E*i*MAS Training Material

COURSE NOTE

Course Title: Operation, Maintenance Record and Inspection of Incinerator

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LEGISLATIVE REQUIREMENTS

MODULE 1

LEGISLATIVE REQUIREMENTS

LEARNING OUTCOMES:

- ✓ Explain the legislative requirements on incinerator plant in Malaysia
- ✓ Able to convert emission concentrations into the desired unit
- ✓ Able to correct emissions to the standard levels

1.1 Legislation, regulation and implementation of regulations on incineration in Malaysia

Installation and operation of incinerator in Malaysia is governed by regulations such as:

a) Environmental Quality (Clean Air)Regulations 1978
b) Environmental Quality (Prescribed Activities) (Environmental Impact Assesment) Order 1987
c) Environmental Quality (Dioxin and Furan) Regulations 2004

1.1.1 Environmental Quality (Clean Air) Regulations 1978

These regulations mention the rules of incinerator under Part III which comes such as follow:

Part III: Burning of waste

7. Burning of trade waste in incinerator only

No owner or occupier of industrial or trade premises shall burn or cause to be burnt combustible materials, refuse and produce or waste except in an incinerator of such type and design approved by the Director-General.

8. Erection of incinerator to obtain prior approval

No person shall erect, construct, install, resite or alter any incinerator without prior written approval from the Director-General.

1.1.2 Environmental Quality (Prescribed Activities) (Environmental Impact Assesment) Order 1987

Under section 34A of the Environmental Quality Act 1974, EIA is required for Prescribed Activities. Construction of incineration plant is a Prescribed Activity under Item 18 (a) and (b), stated as follows:

18. WASTE TREATMENT AND DISPOSAL
  (a) *Toxic and Hazardous Waste –*
    (i) Construction of incineration plant
  (b) *Municipal Solid Waste –*
    (i) Construction of incineration plant

1.1.3 Environmental Quality (Dioxin and Furan) Regulations 2004

These regulations shall apply to the following facilities:

a) Municipal solid wastes incinerator;
b) Scheduled waste incinerator;
c) Pulp or paper industry sludge incinerator; and
d) Sewage sludge incinerator.

The permissible air emission limit for new facilities is stated as follows:
Concentration limit for air emission of dioxin and furan for new facilities shall not exceed 0.1 nanogram/Nm^3 *TEQ.*

1.2 Legislation, regulation and implementation of regulations on incineration in other developed countries

The summary of regulations on incineration in other countries is shown in **Table 1-1**. Some of the regulations are attached in **Appendix A**.

Table 1-1: Regulations on incineration in other countries

Country	Regulation	Note
European Union (EU)	DIRECTIVE 2000/76/EC on the incineration of waste	Covers both incineration and co-incineration plant (facilities whose main purpose is to produce energy)
United States (US)	Clean Air Act (CAA)	Developed specifically for a. Commercial and Industrial Solid Waste Incineration Units (CISWI) b. Hospital/Medical/Infectious Waste Incinerators (HMIWI) c. Other Solid Waste Incineration Units (OSWI)
United Kingdom (UK)	Waste Incineration (England and Wales) Regulations 2002	
Taiwan	Air Pollution Control Act	There are 2 emission standards for incinerator: a. Waste Incinerator Air Pollutant Emissions Standards b. Waste Incinerator Dioxin Control and Emission Standards

1.3 Comparison of emission standards

The comparison of emission standards in Malaysia, EU, USA and Taiwan is shown in **Table 1-2**.

Table 1-2: Incinerator emission standards in Malaysia, EU, USA and Taiwan

Pollutant	Malaysia*		EU*		USA^	Taiwan^^
	Limit	Monitoring	Limit	Monitoring	Limit	Limit
Total dust	N.A	N.A	10## mg/Nm^3	Continuous	N.A	N.A
Total Organic Carbon	N.A	N.A	10## mg/Nm^3	Continuous	N.A	N.A
Total PM	100 mg/Nm^3	Continuous	N.A	N.A	70 mg/Nm^3	N.A
NMVOC as total C	10 mg/Nm^3	Continuous	N.A	N.A	N.A	N.A
Hydrogen chloride (HCl)	40 mg/Nm^3	Continuous	10 ## mg/Nm^3	Continuous	62 ppmv^^	40ppm
Hydrogen fluoride (HF)	1 mg/Nm^3	Continuous	1 (2) ### mgNm^3	Continuous	N.A	N.A
Sulphur dioxide (SO$_2$)	50 mg/Nm^3	Continuous	50## mg/Nm^3	Continuous	20ppmv^^	80ppm
Nitrogen oxides (NO$_2$)	200 mg/Nm^3	Continuous	200*** mg/Nm^3	Continuous	388ppmv^^	180ppm
Carbon monoxide (CO)	50 mg/Nm^3	Continuous	50# mg/Nm^3	Continuous	157ppmv^^	120ppm
Cadmium (Cd)	-	-	-	-	0.004 mg/Nm^3	0.02 mg/Nm^3
Cadmium (Cd) & Thallium (TI)	0.05 mg/Nm^3	Periodic**	0.05 mg/Nm^3	Periodic**	-	
Mercury (Hg)	0.05 mg/Nm^3	Periodic**	0.05 mg/Nm^3	Periodic**	0.47 mg/Nm^3	0.05 mg/Nm^3
Lead (Pb)	N.A	N.A	N.A	N.A	0.04 mg/Nm^3	0.2 mg/Nm^3
Antimony (Sb), Arsenic (As), Lead (Pb), Chromium (Cr), Cobalt (Co), Copper (Cu), Manganese (Mn), Nickel (Ni), Vanadium (V)	0.5 mg/Nm^3	Periodic**	0.5 mg/Nm^3	Periodic**	N.A	N.A
PCDD/PCDF	0.1 ng TEQ/Nm^3	Periodic**	0.1 ng TEQ/Nm^3	Periodic**	0.41 ng TEQ/Nm^3	0.1 ng TEQ/Nm^3
Opacity	-	-	-	-	10%	10%

Notes:

*	O_2 reference content is 11%.
**	average value over sampling period of a minimum of 30 minutes and a maximum of 8 hours
***	daily average value and half-hourly (97% comply) average value , value for incineration plants with capacity of exceeding 6 tonnes/hour or new plant
#	daily average value
##	daily average value and half-hourly (97%) average value
###	daily average value is address as normal while half-hourly (97%) average value is address in bracket
^	O_2 reference content is 7%, based on 2000 Commercial and Industrial Solid Waste Incineration Units (CISWI) limit for performance test.
^^	O_2 reference content is 11%, based on general industrial waste incinerator (newly built), handling capacity of 10 tons or more per hour. All values are the average value of sampling times that are standard in a test method.
N.A	Not available

1.4 Unit conversion

As shown in **Table 1-2**, incinerator emission limits from different countries are presented in different expressions. Similar situation is sometimes found when reading emission testing report. For example, some express the concentrations as ppmv and some express the concentrations as mg/m^3. There is also situation where the pollutant concentrations need to be adjusted or corrected to reference conditions of oxygen content, carbon dioxide content and moisture content. The following sections present useful unit conversion that might be needed when dealing with incinerator emissions.

1.4.1 Systems of Unit

The SI units stand for International System of Units, which is the modern form of the metric system (centimetre gram second, CGS) and widely applied all over the world except United States of American which remains customary units (English units) in their system of measurement.

Under the SI units, a set of unit prefixes known as SI prefixes is specified to precede a basic unit of measure to indicate a decimal, multiple or fraction of the unit as shown in **Table 1-3**.

Table 1-3: SI prefixes

Prefix	**Symbol**	**Magnitude**	**Factor**
Exa	E	1 000 000 000 000 000 000	10^{18}
Peta	P	1 000 000 000 000 000	10^{15}
Teta	T	1 000 000 000 000	10^{12}
Giga	G	1 000 000 000	10^{9}
Mega	M	1 000 000	10^{6}
Kilo	K	1000	10^{3}
Milli	m	0.001	10^{-3}
Micro	µ	0.000 001	10^{-6}
Nano	n	0.000 000 001	10^{-9}
Pico	P	0.000 000 000 001	10^{-12}
Femto	f	0.000 000 000 000 001	10^{-15}
atto	a	0.000 000 000 000 000 001	10^{-18}

1.4.2 Converting air pollutant concentrations

The conversion equations depend on the temperature at which the conversion is wanted (usually about 20 to 25°C). At an ambient air pressure of 1 atm, the general equation is:

$$\text{ppmv} = \text{mg/m}^3 \text{ x } \frac{0.08205 \text{ x } T}{M}$$ **Equation 1-1**

And for the reverse conversion is:

$$\text{mg/m}^3 = \text{ppmv x } \frac{M}{0.08205 \text{ x } T}$$ **Equation 1-2**

Where:

ppmv = air pollutant concentration, in parts per million by volume
mg/m^3 = milligrams of pollutant per cubic meter of air
T = atmospheric temperature in Kelvins = 273.15 + °C
0.08205 = Universal Gas Law constant in atm.L/mol.K
M = molecular weight of the air pollutant (g/mol)

1.4.3 Normalisation

Measured emission levels must be normalized or corrected to standard or reference levels to negate the effect of dilution. Normalizing the data can have a profound effect on the measured levels, particularly when normalizing for oxygen. The equations used to normalize the measurements to standard or reference conditions are given below.

1.4.3.1 Normalisation to standard conditions

The standard conditions for gases are shown in **Table 1-4**. Gas volume measured or normalized at 0°C and 1 atm is expressed as normal cubic meter (Nm^3).

Table 1-4: Standard conditions for gases

System	T_S	P_S	V_S	n_S
SI	273 K	1 atm	0.022415 m^3	1 mol
CGS	273 K	1 atm	22.415 L	1 mol

Note: 1 kmol of any ideal gas equals to 22.415 Nm^3 of that gas at 0 °C and 1 atm of absolute pressure

The following equations are used to normalize pollution concentrations to standard temperature and pressure:

$$\frac{mg}{m^3}\text{(normalised)} = \frac{mg}{m^3}\text{(measured) x } \frac{\text{temperature (°C)}_{\text{(measured)}} + 273}{\text{temperature (°C)}_{\text{(standard)}} + 273} \quad \textbf{Equation 1-3}$$

$$\frac{mg}{m^3}\text{(normalised)} = \frac{mg}{m^3}\text{(measured) x } \frac{\text{pressure}_{\text{(standard)}}}{\text{pressure}_{\text{(measured)}}} \quad \textbf{Equation 1-4}$$

1.4.3.2 Correcting to a dry basis

The following equation is used to correct gas volume to dry basis:

$$\text{dry basis concentration} = \frac{(\text{wet basis concentration})}{(1 - \text{w})} \qquad \textbf{Equation 1-5}$$

w = fraction of water vapor by volume in the emitted exhaust gas

Example:

Determine dry basis concentration for 50 ppmv gas having 10 volume percent water vapor.

$$\text{Dry basis concentration} = \frac{50}{1-0.1} = 55.55 \text{ ppmv}$$

1.4.3.3 Correcting to reference oxygen content

The following equation can be used to correct a measured pollutant concentration in a emitted gas to an equivalent pollutant concentration in an emitted gas containing a specified reference amount of O_2:

$$C_r = C_m \text{ x } \frac{(21 - O_2 \text{ reference})}{(21 - O_2 \text{ measured})} \qquad \textbf{Equation 1-6}$$

C_r = corrected concentration of a dry gas with a specified reference volume % O_2

C_m = measured concentration in a dry gas having a measured volume % O_2

Example:

Given SO_2 concentration of 40 ppmv with measured oxygen content of 10%, correct to 6% O_2.

Solution:

$$C_r = 40 \text{ x } \frac{(21 - 6)}{(21-10)} = 54.5 \text{ ppmv corected to 6\% } O_2$$

1.4.3.4 Correcting to reference carbon dioxide content

The following equation can be used to correct a measured pollutant concentration in an emitted gas (containing a measured CO_2 content) to an equivalent pollutant concentration in an emitted gas containing a specified reference amount of CO_2:

$$C_r = C_m \text{x} \frac{(\text{reference volume} \%CO_2)}{(\text{measured volume} \% \, CO_2)} \qquad \textbf{Equation 1-7}$$

C_r = corrected concentration of a dry gas having a specified reference volume % CO_2

C_m = measured concentration of a dry gas having a measured volume % CO_2

Example:

Correct a measured particulates concentration of 200 mg/m^3 in a dry gas that has a measured 8 volume % CO_2 to 12 % CO_2.

$$C_r = 200\text{x}\left(\frac{12}{8}\right) = 300 \text{mg/m}^3$$

1.4.4 Percentage, ppm and ppb conversion

Expressions such as ppm and ppb are used when pollutant concentration is very low.

ppm	=	part per million	ppb	=	part per billion
1 ppm	=	1 part in million	1 ppb	=	part in billion
	=	$\frac{1}{1,000,000}$		=	$\frac{1}{1,000,000,000}$
	=	0.000 001		=	0.000 000 001

Unit of ppm and ppb can also be expressed in percentage using conversion shown in **Table 1-5**

Table 1-5: Conversion of ppm and ppb to percentage

ppm	ppb	Percentage
0.001	1	0.000 000 1
0.01	10	0.000 001
0.1	100	0.000 01
1	1 000	0.000 1
10		0.001
100		0.01
1000		0.1
10 000		1

Conversion from percentage to ppm:

$$1\% = \frac{1}{10^2}, \quad 1 \text{ ppm} = \frac{1}{10^6}$$

$$1\% = \frac{1}{10^2} = \frac{10^4}{10^6} = 10^4 \text{ ppm}$$

1.5 Overview of all current and future standards

To date, there is no specific regulation on incinerator in Malaysia. The air emission limits for incinerator are subjected to Clean Air Regulation (CAR) which is not sufficient for incinerator. However, with the listing of incineration plant under prescribed premises, DOE can prescribe any operating standard necessary for incinerator operation and can take action on non compliance by plant operator.

Currently, new CAR is being drafted with the limits for incinerator plants are as shown in **Figure 1-1**.

FOURTEENTH SCHEDULE

(Regulation 11)

Waste Incinerators (all sizes)

Air pollutant emission from incineration process shall not exceed the concentration limits tabulated below.

The O_2 reference content is 11%.

Pollutant	Limit value	Monitoring
Total PM	100 mg/m^3	continuous
NMVOC as total C	10 mg/m^3	continuous
Hydrogen chloride (HCl)	40 mg/m^3	continuous
Hydrogen fluoride (HF)	1 mg/m^3	continuous
Sulphur dioxide (SO_2)	50 mg/m^3	continuous
Nitrogen oxides, expressed as nitrogen dioxide (NO_2)	200 mg/m^3	continuous
Carbon monoxide (CO)	50 mg/m^3	continuous
Cadmium and its compounds, expressed as cadmium (Cd) Thallium and its compounds, expressed as thallium (Tl)	total 0.05 mg/m^3	periodic 1)
Mercury and its compounds, expressed as mercury (Hg)	0.05 mg/m^3	periodic 1)
Antimony (Sb), Arsenic (As), Lead (Pb), Chromium (Cr), Cobalt (Co), Copper (Cu), Manganese (Mn), Nickel (Ni), Vanadium (V), and their compounds expressed as the element	total 0.5 mg/m^3	periodic 1)
PCDD/PCDF	0.1 ng TEQ/m^3	periodic 1)

1) Average values over the sampling period of a minimum of 30 minutes and a maximum of 8 hours

SO_2 and SO_3, expressed as SO_2

NO and NO_2, expressed as NO

Figure 1-1: New CAR for incinerator plant

MODULE 2

OVERVIEW OF INCINERATOR

MODULE 2

OVERVIEW OF INCINERATOR

LEARNING OUTCOMES:

- ✓ Describe the type of incinerators available commercially
- ✓ Discuss the commercial application of various type of incinerators
- ✓ Explain the strength and weaknesses of different type of incinerators
- ✓ Identify other thermal destruction processes

2.1 Introduction

This module provides an overview of incinerator which includes the types of incinerator and their application. Incinerator has evolved from a bad-perceived waste disposal facility into a modern, clean and can even be located in the middle of busy city as shown in **Figure 2-1** and **Figure 2-2**.

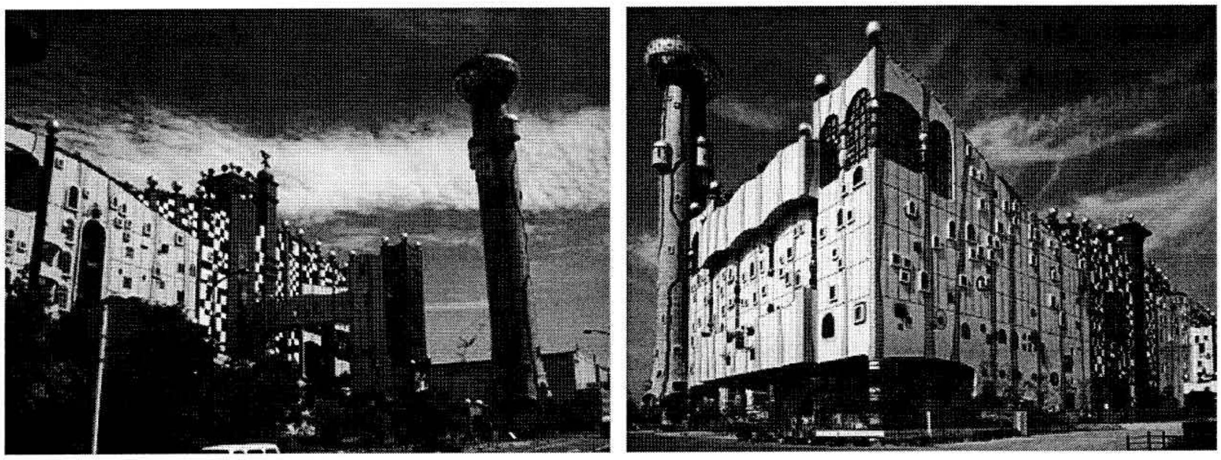


Figure 2-1: Maishima incinerator plant (capacity of 900 tonnes/day) in Osaka, Japan (the plant is decorated by Friedensreich Hundertwasser, an artist from Austria)

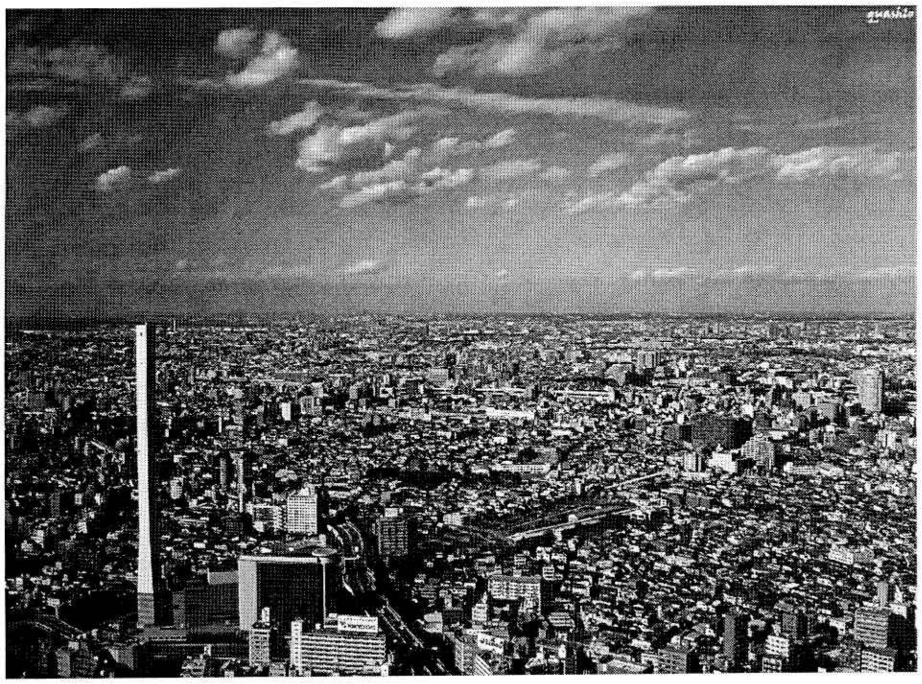


Figure 2-2: Incinerator plant in Tokyo, Japan

2.2 Type of Incinerators

There are several types of incinerators available in the market and the choice of selection depends on several factors such as the availability and type of fuel to be burnt, eg; biomass, municipal solid waste, clinical waste, etc as well as design and operating factors. Economic consideration is also part of the decision making process in evaluating the most suitable incinerator for a particular project. The combustor is where the combustion of fuels (biomass, coal, municipal solid waste, etc) takes place.

Combustors for biomass and municipal solid waste are predominantly either grate-fired system or fluidized bed. Biomass is generally fed into the fluidized bed. Past practices showed that municipal solid waste is normally incinerated in a grate-firing system, whereas processed municipal solid waste or also known as refused derived fuel (RDF) is commonly burnt in a fluidized bed. Grate-firing systems are equipped with flat or sloping grates. The grates may either be moving or stationary in design. Grate-firing reactors were the most versatile units in the mid 1980s. Rotary kiln incinerators operate by rotating the waste in an inclined cylindrical container. The kiln rotates as to ensure thorough mixing of the waste with air. Rotary kiln has been used to incinerate large quantities of sludge, liquid and solid wastes.

2.2.1 Moving Grate Incinerator

In a traveling grate combustion system, the waste is burnt in a bed that gradually moves down the grate from waste inlet to ash exit. The primary air is introduced under the grate so that it flows through the bulk of the waste in the furnace. The secondary air inlet is normally located above the grate to facilitate complete combustion. The waste incineration is normally carried out in three stages, namely drying, combustion and burnout stages in which combustion air is regulated differently at these stages.

The commonly used moving grate incinerator is reciprocal type where the movable and fixed fire grates are placed alternately and mounted to movable and fixed frames respectively, as shown in **Figure 2-3**. The movable frame is hydraulically driven so that the movable grates make a reciprocal vertically oblique motion. Because the sliding area of each fire grate is constantly cleaned by the fire grate itself, clogging and sticking of molten aluminum are prevented.

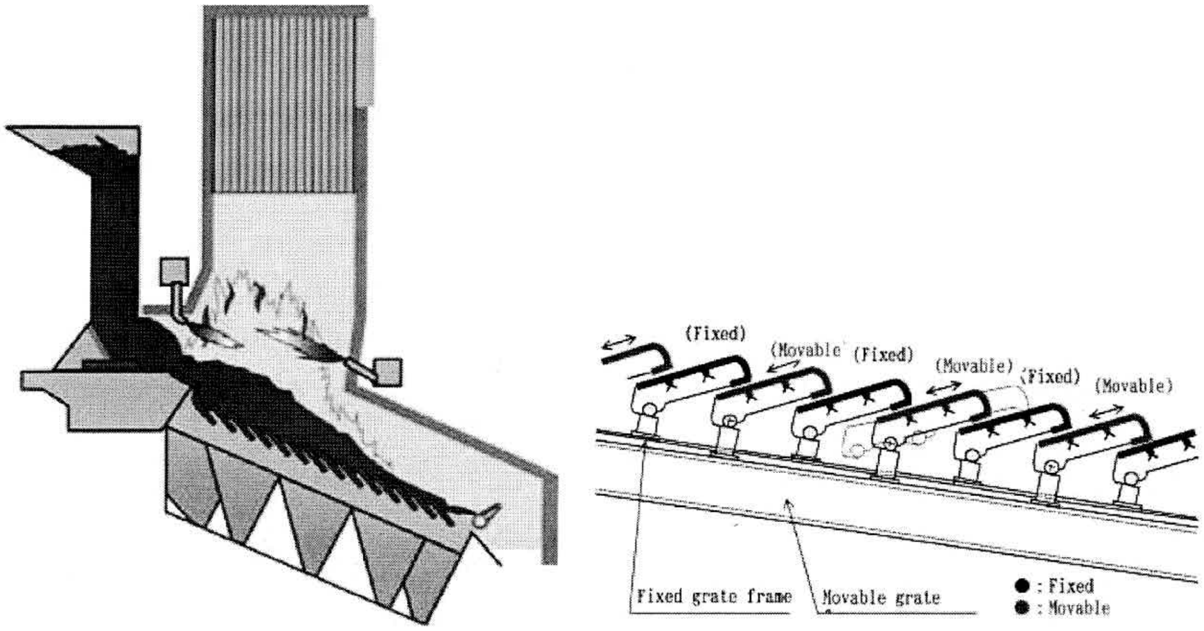


Figure 2-3: Schematic diagram of reciprocal grate incinerator

2.2.2 Step Hearth Incinerator

Step hearth incinerator comprises of a series of concrete steps of three separate hearths which is also known as the primary chamber. The hearth is embedded with primary air channels. The waste is forced into the combustion area by the ram loader or screw feeder. The burning takes place on the hearths in which drying, actual combustion and burnout stages is carried out with different air intake onto this individual hearth. The first hearth is supplied with sub-stoichiometric oxygen during which most volatile are driven out from the waste. The second hearth is where the main combustion happens and the finally the third hearth is used for the final stage of burnout of fixed carbon. The waste is burned while it is pushed off of different level hearths by means of a hydraulic ram. The ash is finally discharged out of the system for disposal. Normally the system is equipped with a secondary chamber for complete volatile combustion. **Figure 2-4** shows a diagram of a step hearth incinerator.

Currently, Pantai Medivest (Melaka) and Faber Mediserve Sdn Bhd (Perak) are using step hearth incinerator for hospital wastes.

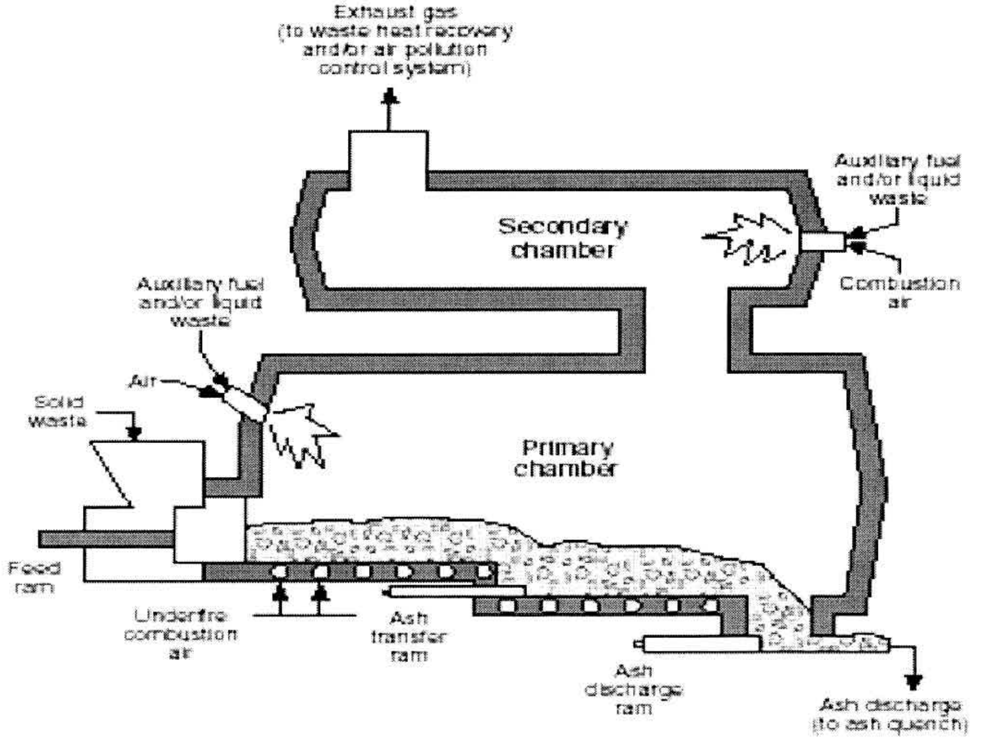


Figure 2-4: Schematic diagram of a step hearth incinerator

2.2.3 Rotary Kiln Incinerator

Incineration in a rotary kiln incinerator normally consists of a two stage process consisting of a kiln as the first combustion chamber and volatile gas combustion in the secondary chamber. The kiln is slightly inclined downwards from the feed inlet and rotates slowly about its cylindrical axis. The rotation of the kiln enables the waste and air to mix thoroughly for the optimum heat transfer and combustion to take place. The ash is continuously evacuated at the bottom end of the kiln. Residence time of the waste inside the kiln may be changed by regulating the kiln's rotational speed. Due to the absence of any moving part and metal surface inside the kiln, rotary kilns are normally able to operate at high temperature. A rotary kiln is the most versatile incinerator which can treat a large range of wastes, varying from low to high calorific values. The system must be equipped with a flue gas treatment system before releasing the flue gases to the atmosphere. **Figure 2-5** shows a schematic diagram of a rotary kiln incinerator.

Rotary kiln incinerator is currently being used by Kualiti Alam (Negeri Sembilan) and Radicare Sdn Bhd (Selangor) for hazardous waste and hospital waste respectively.

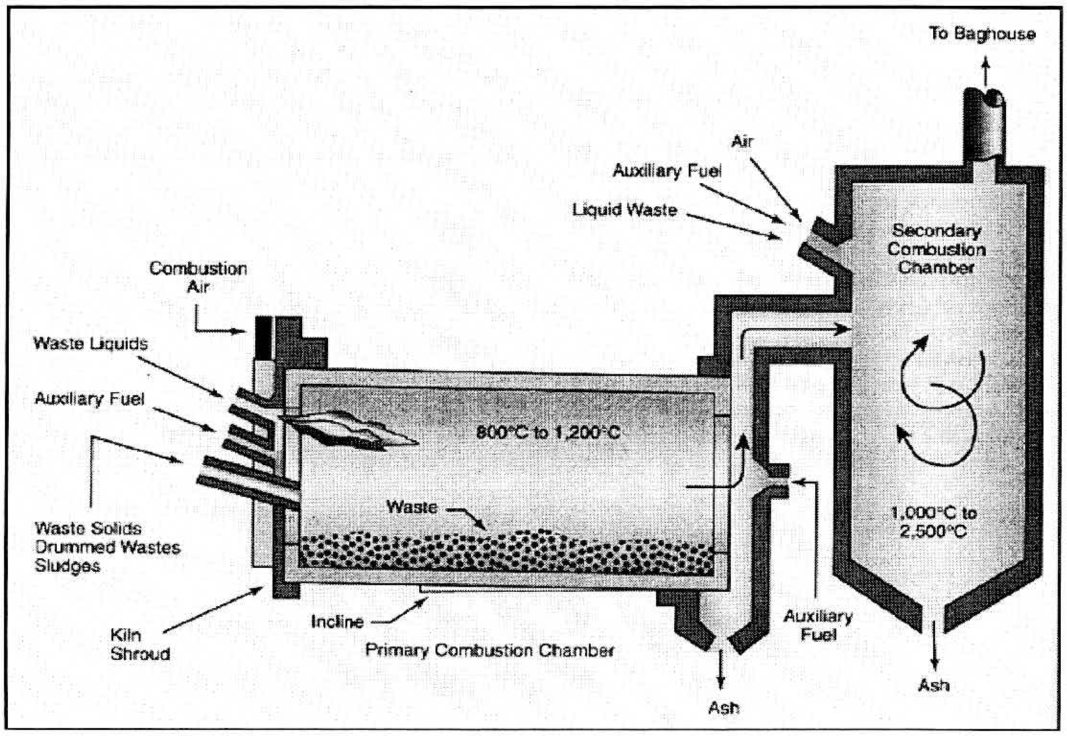


Figure 2-5: Schematic diagram of a rotary kiln incinerator

2.2.4 Fluidized Bed

Fluidized bed technology has been used extensively in recent years to burn variety of solid wastes. These include sludge, biomass, coal, refused derived fuel (RDF), mixed wastes of paper and plastic and as a combined fuel in co-combustion of primary fuel. It has gained tremendous acceptance in the recent years due to several reasons. One of them is the ability to burn various types of fuels because it provides long fuel residence times, good contacting of fuel and bed material with air with a relatively uniform temperature distribution inside the bed.

In the fluidized bed system, the bed is first heated close to the operating temperature. The bed material, usually sand, absorbs and stores the heat, while the turbulence and mixing of the bed keeps the temperature uniform throughout the bed. When waste is introduced into the fluidized bed, the high heat and mass transfer characteristics of the bed permits the rapid energy conversion at practically isothermal condition. The high surface area available in fluidized beds on which reactions could occur, result in good conversion efficiency, higher throughput and lower operating temperature. Uniform temperatures and high heating capacities of sand permits a wide range of low-grade fuels of even non-uniform size and varying moisture content to be converted to desired products.

Two types of fluidized beds are bubbling fluidized bed (BFB) and circulating fluidized bed (CFB). In the bubbling fluidized bed (BFB) combustor, the majority of fuel particles which are fed onto the bed react in the bed with the oxygen in the upward airflow (primary air). Therefore, the lower combustion zone contains a high density of the fuel and during the combustion, the bed acts as a heat buffer enabling high heat transfer between the particles. Due to this, the BFB could tolerate larger fuel size (0 – 50 mm) than the CFB combustor and the BFB combustor is also less sensitive to variations in the fuel moisture content and it is suitable for waste with wide variation of moisture contents. The mass concentration of fine particles is less in the BFB compared to that of the CFB due to the lower application of the fluidization number in the BFB. The BFB combustor operates at lower fluidization velocity, typically 1-3 m/s whereas the CFB combustor operates at higher fluidization velocity ranges from 3 – 10 m/s. As a result of the higher fluidization velocity in the CFB combustor, solids are entrained in the air flow more equally along the combustor height and the heat transfer and combustion temperature is more equally distributed with the combustor height compared to the BFB. With an increase in the mass load of the elutriated fine particles, the design of the cyclone separator would be larger in the CFB than in the BFB. Thus, increasing the investment cost of the CFB system. In the CFB combustor, the major portions of the dust and unconverted carbon in the product gas are recycled to the reactor bottom through a cyclone, thus leading to high carbon conversion. The schematic diagram of the bubbling fluidized bed combustor is shown in **Figure 2-6**. **Figure 2-7** illustrates the photograph of pilot scale fluidised bed.

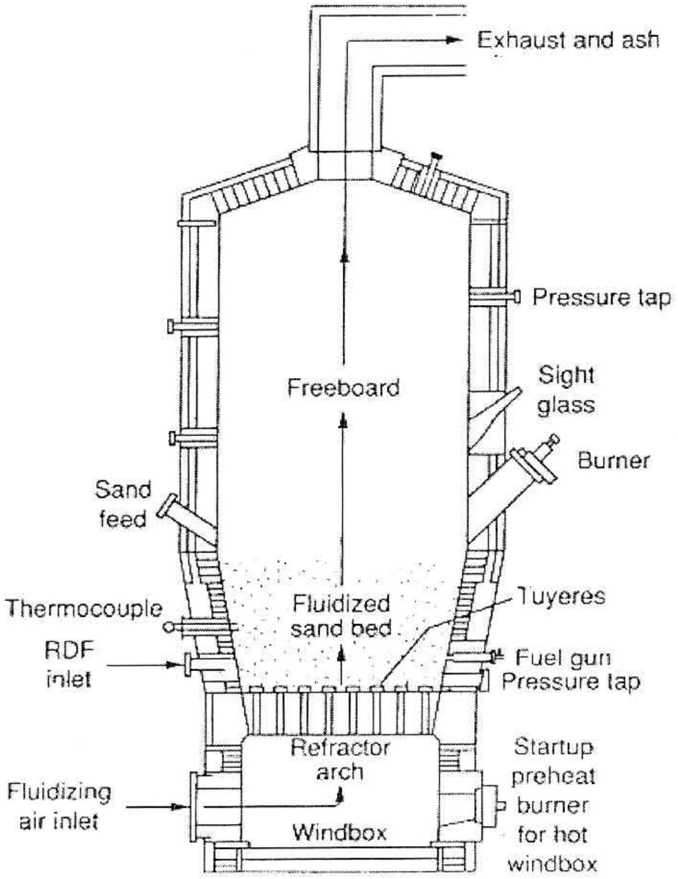


Figure 2-6: Schematic of bubbling fluidized bed combustor

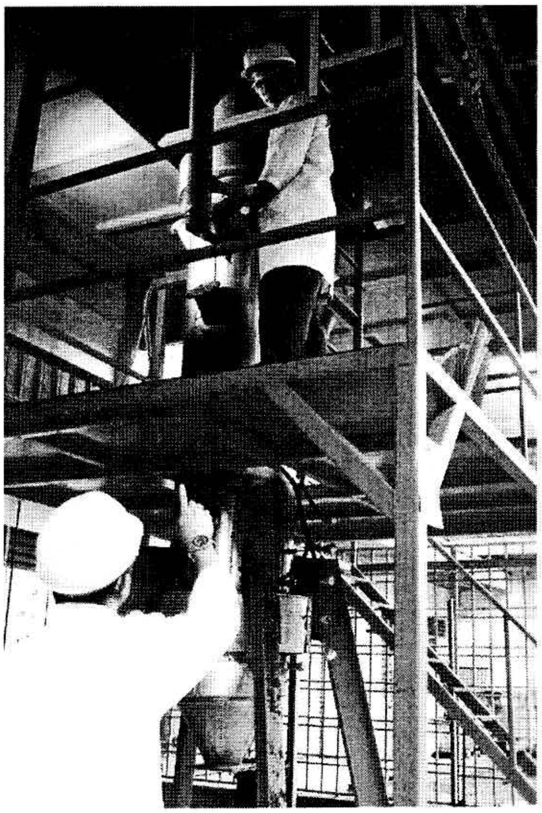


Figure 2-7: Photograph of pilot scale fluidised bed in Universiti Teknologi Malaysia

2.2.5 Specialized Incinerator

Liquid Injection Incinerators are used for hazardous chemical waste incineration. It also can be used to dispose of any combustible liquid and liquid-like waste (slurries and sludges). The system utilizes high pressure to prepare liquid wastes for incineration by breaking them up into tiny droplets and mix with the combustion air. The mixture of waste fumes and air ignite in the combustion chamber. Typical combustion residence time and temperature ranges are 0.5 to 2 seconds and 700^0C – 1600^0C to ensure complete liquid waste combustion. If the energy content of the liquid waste is not high enough to maintain the combustion temperature, a supplemental fuel such as fuel oil or natural gas is provided. Schematic diagram of a liquid incinerator is shown in **Figure 2-8.**

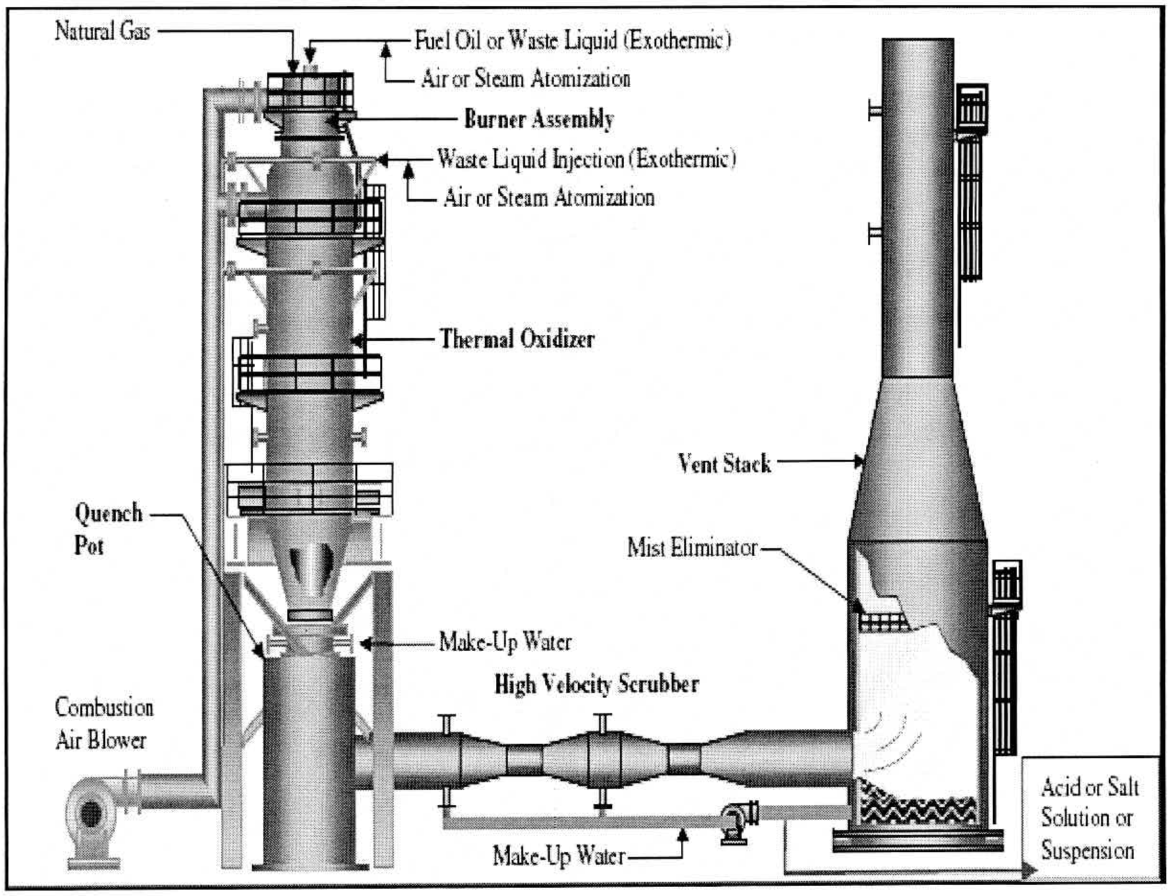


Figure 2-8: Schematic diagram of a liquid incinerator

2.3 Commercial Application of Incinerators

Incinerators have been widely used in several different types of application such as in the combustion of municipal solid wastes, clinical waste, sewage sludge, animal carcass and chemical wastes (liquid or solid waste). **Table 2-1** summarizes the most suitable types of combustion technologies for the application in waste incineration.

Table 2-1: Application of incinerators in waste incineration (IPC Guidance Note, 1996)

	Wastes				
Combustion technologies	**Chemical**	**Clinical**	**Municipal**	**Sewage sludge**	**Animal carcass**
Fixed hearth	√	√			√
Moving hearth		√	√		
Rotary kiln	√	√	√	√	√
Fluidized bed			√	√	
Liquid injection	√				

Moving hearth incinerator for municipal solid waste is depicted in **Figure 2-9**. The waste is discharged from trucks to a pit where a crane transfers it to the feed hopper from which it is fed onto the combustion grate in a primary combustion chamber.

The rotary kiln system is highly versatile as it is capable of burning all types of waste. Solid waste is usually fed by the ram feeding system into the chamber whilst sludges, liquids and gases are injected through nozzles located in the front or rear face of the kiln or in the afterburner. **Figure 2-10** shows a mass burn rotary kiln for incineration of municipal solid waste.

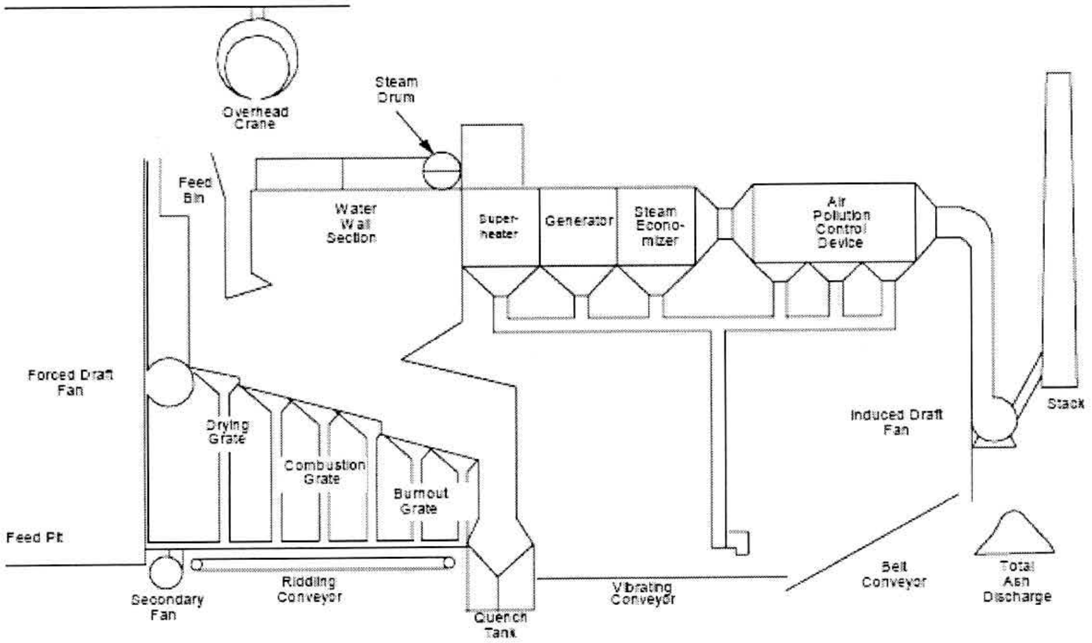


Figure 2-9: Mass burn incinerator of municipal solid waste incineration

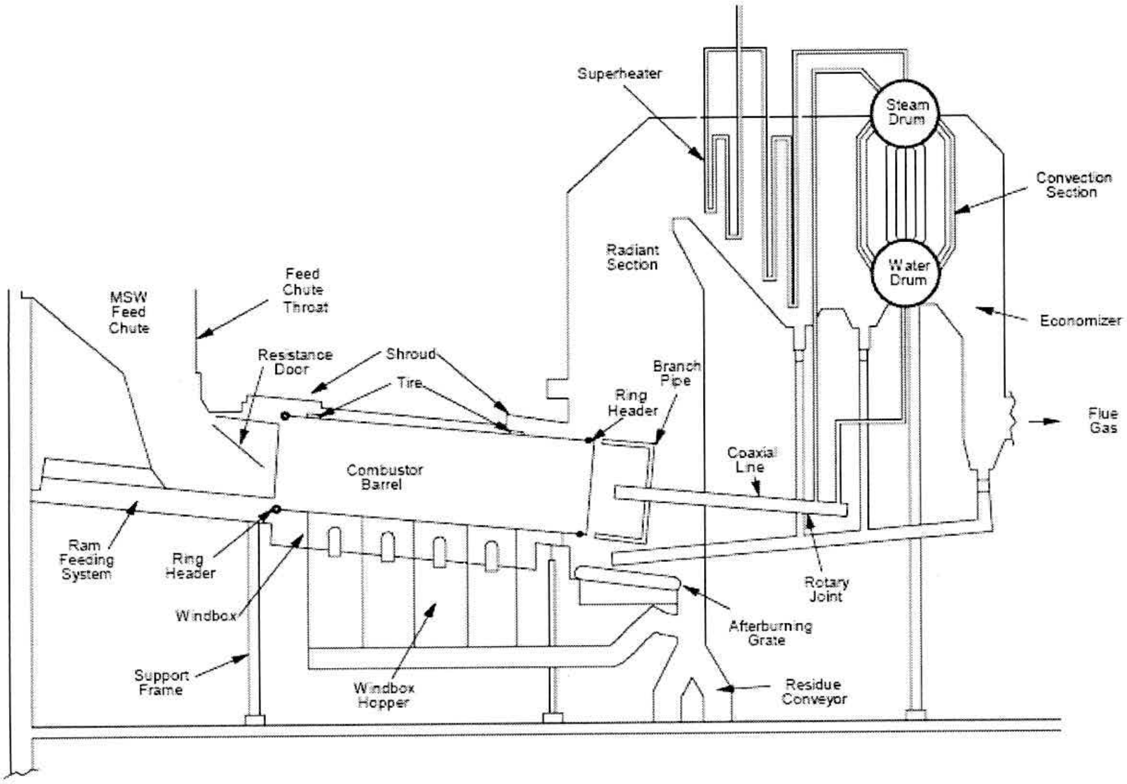


Figure 2-10: Mass burn rotary kiln incinerator

The selection of type of incinerator is however depended on many factors such as feedstock availability, heat and power generation, economic consideration, etc. Several heat and power generation plants and palm oil mills are using municipal solid waste, refuse derived fuels (RDF) as well as biomass waste for power generation. RDF and biomass are most likely to be used in fluidized bed combustors as the waste is homogeneous in nature.

2.4 Advantages and Disadvantages of Types of Incinerators

All types of incinerator have their own strengths and weaknesses as shown in **Table 2-2.**

Table 2-2: Strength and weakness of different types of incinerators

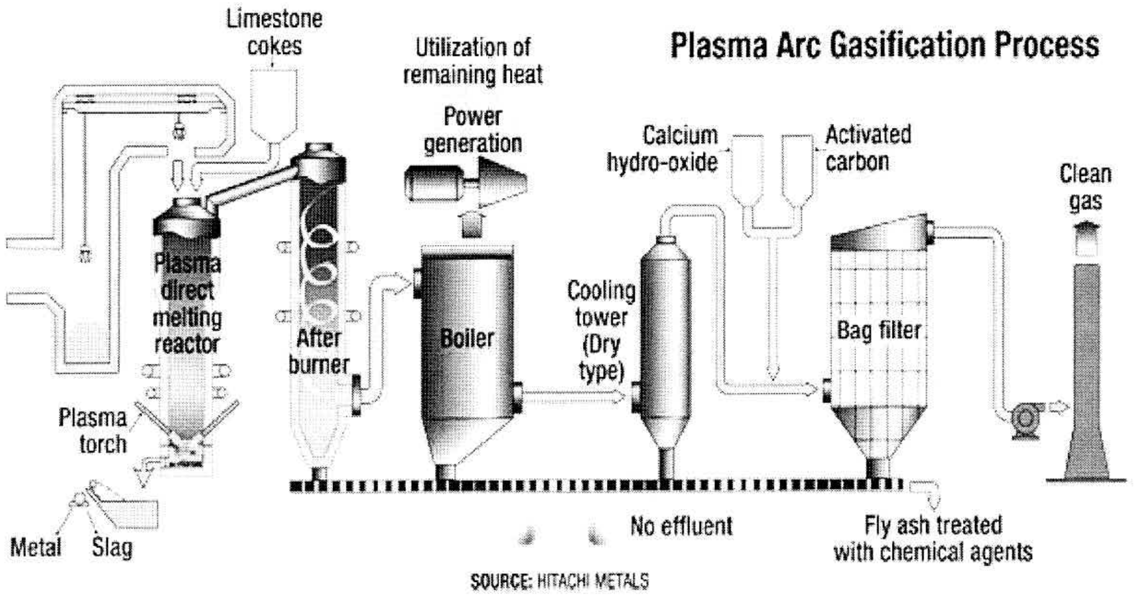
Incinerator type	Strength	Weakness
Grate furnaces (Step Hearth and Moving grate)	Low ash carry over during the operation	Higher excess oxygen decreases efficiency
	High ash content feedstock possible	Poor heat transfer, combustion conditions not homogeneous
	Low dust load in the flue gas	Possible ash agglomeration and clinker formation on grate. Damage to the grate
Fluidized bed	Good temperature distribution	High energy requirement for blower/compressor for fluidizing air
	No hot spot	High dust and particulate in flue gas
	Good gas and solid mixing	Erosion of internals resulting from high solid velocities in the CFB
	Low tar content in product gas	Possibility of de-fluidization due to agglomeration of solid in the Bubbling Bed

Incinerator type	Strength	Weakness
	High carbon conversion efficiency	Added complexity in designing and operating the re-circulating loop for CFB
	Tolerate wide variations of fuel quality	Low capital cost for CFB
Rotary Kiln	Ability to incinerate a variety of waste streams; solid, liquid, sludge, gas	Relatively high particulate carryover to the gas stream
	Readily controlled residence time of solid in kiln	A separate afterburner is required for destruction of organics in the off gas stream
	High turbulence and effective contact with air/gas within the kiln	Relatively high amount of excess air is required
	Availability of many types of feed mechanisms (ram feeder, screw feeder, direct injection)	Relatively expensive to purchase and to maintain due to its mechanisms involved in its motion. Difficult to maintain air seal, thus difficult to control oxygen level in combustion chamber.

2.5 Other Technique of Thermal Destruction Process

Plasma technology is the most recent thermal destruction method for waste decomposition. The system employs limited air supply (starved air) into the chamber and the operation is conducted at a very high temperature. The electrical current is constantly supplied through the plasma generation system and the heat generated from the plasma torch is used to thermally dissociate the waste materials into synthesis gas (CO, H_2, trace amount of methane) or even into its elemental forms depending on the predetermined operating temperature. The constant high temperature operations ensure complete destruction of all complex organic compounds and through the use of high technology control process minimizes the reformation of complex pollutants and hazardous materials. Some commercial plasma technology providers have reported to achieve temperature of up to 5000^{0}C of their plasma torch arc.

The application of plasma technology has also been widely used in the production of the synthesis gas which has the calorific values comparable to the existing fuel gas. The air pollution control is similar to the existing conventional system which consists of bag filter, electrostatic precipitator (ESP) and other forms of air pollution control equipments. The byproduct of the plasma heating is slag and known to have commercial value in the construction industries. Typical waste reduction via plasma technology is illustrated in **Figure 2-11**. In this process, a partial oxidation/limited air (gasification) is supplied through the plasma torch.



SOURCE: HITACHI METALS

Figure 2-11: Plasma arc gasification process

MODULE 3

INCINERATOR DESIGN PRINCIPLES

MODULE 3

INCINERATOR DESIGN PRINCIPLES

LEARNING OUTCOMES:

- ✓ Explain the basic terminologies of thermal destruction of waste in an incinerator
- ✓ Describe the fundamental of design and operating parameters in the incineration processes
- ✓ Discuss the components of incinerator such as fuel feeding system, combustor and air pollution control system
- ✓ Carry out and perform the mass and energy balance in an incinerator process

3.1 Introduction

This module focuses on the design and operating parameters of an incinerator. Factors such as residence time, air and temperature requirement during combustion processes are discussed. Furthermore, basic terminologies of the burning process are introduced such as incineration, combustion, gasification and pyrolysis. The concept of complete and incomplete combustion as well as its products gases is also highlighted such as Product of Incomplete Combustion (PICs) and Principle Organic Hazardous Constituents (POHCs). Finally thermodynamics properties of the incineration process are discussed such as the waste heating values, adiabatic flame temperature and the incinerator's heat transfer mechanism.

3.2 Terminologies for Incinerators

Some basic terminologies of the waste thermal degradation process are listed and explained as follows:-

3.2.1 Incineration

Incineration is a destruction of waste by burning. It is an exothermic process which releases heat. In theory, incineration of carbon-containing compounds occurs in three steps. The initial process is drying and evaporation of water from the solid matrix, followed by the de-volatilization of volatiles. Volatile matters consist of carbon, hydrogen and oxygen compounds and are released during at the second stage of the burning process. In the absence of oxygen, the gaseous volatiles are assumed to consist of hydrocarbons, C_xH_y and carbon monoxide. The final stage happens after the moisture and volatile matters have been driven off in which the remaining solid is converted to ash via oxidation and gasification reactions.

3.2.2 Combustion

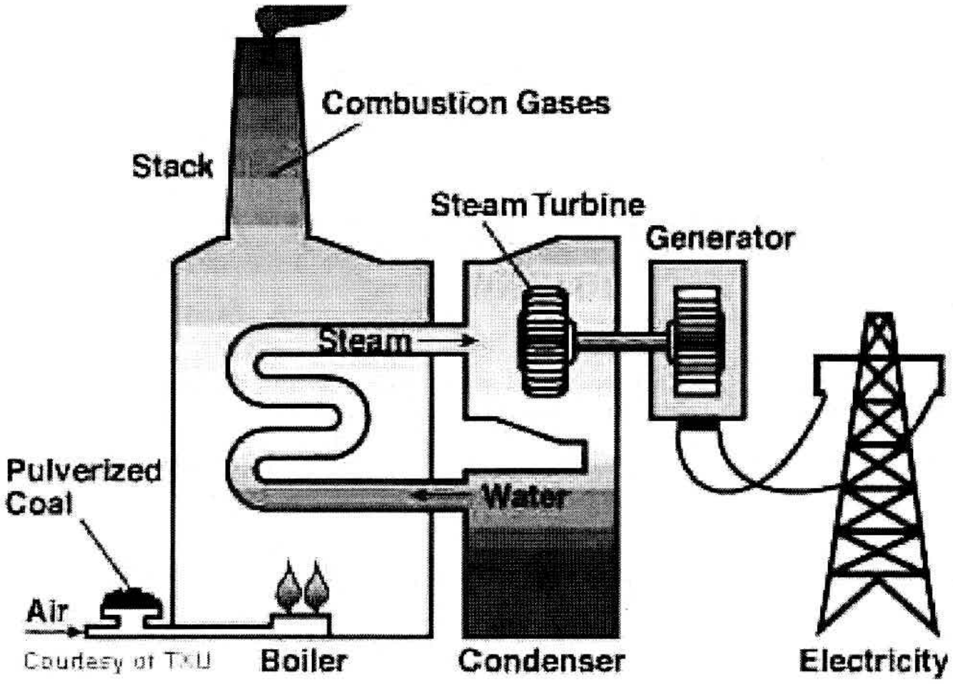
Combustion is a burning of fuel for energy generation. The process is an exothermic reaction and is carried out at excess air. It can be expressed in terms of fundamental chemical reaction equations as follows:

$$C + O_2 \longrightarrow CO_2$$

$$2H_2 + O_2 \longrightarrow 2H_2O$$

These equations state that one mole of carbon reacts with one mole of oxygen to form one mole of carbon dioxide. It also states that two moles of hydrogen react with one mole of oxygen to produce two moles of water. All feed substances that undergo the combustion process are called the reactants and the substances that result from the combustion are known as the products. Theoretically, if the products of the combustion process are carbon dioxide and water, the reactions are said be at stochiometric condition or complete combustion.

Combustion process is commonly used to burn fuels such as municipal solid waste, biomass and coal for the purpose of power generation. The power plant is equipped with power generation devices such as steam and gas turbines for electricity generation. **Figure 3-1** shows the simplified diagram of electricity generation plant using coal as a fuel.



Courtesy of TXU

Figure 3-1: Electricity generation plant with coal as a fuel

3.2.3 Gasification

Gasification is a burning of fuel for energy generation and the process is an exothermic reactions. In contrast to combustion, gasification reactions employ process partial oxidation reactions to carbon monoxide and hydrogen gas. The most important reactions are;

Partial oxidation: $$C+\frac{1}{2}O_2 \rightarrow CO$$

Water gas reaction: $$C+H_2O \longleftrightarrow CO$$

CO shift reaction: $$CO+H_2O \longleftrightarrow CO_2+H_2$$

Steam methane reforming reaction: $$CH_4+H_2O \longleftrightarrow CO+3H_2$$

Gasification reactions represent incomplete combustion where carbonaceous compounds are not fully converted to carbon dioxide and water. Factors that leads to incomplete combustion include poor mixing, too little air and also low operating temperature. Gasification process is performed at lower operating temperature than the combustion process, typically around 850°C.

The gasification process has been used to burn many type of wastes such as municipal solid waste and biomass waste. Its end-gas product is known as a synthesis gas (syngas) and it is used for the production of chemicals. Other useful application of the gasification process is in the production of hydrogen gas as well as in the power generation. **Figure 3-2** shows the possible application of gasification of wastes in the commercial sectors.

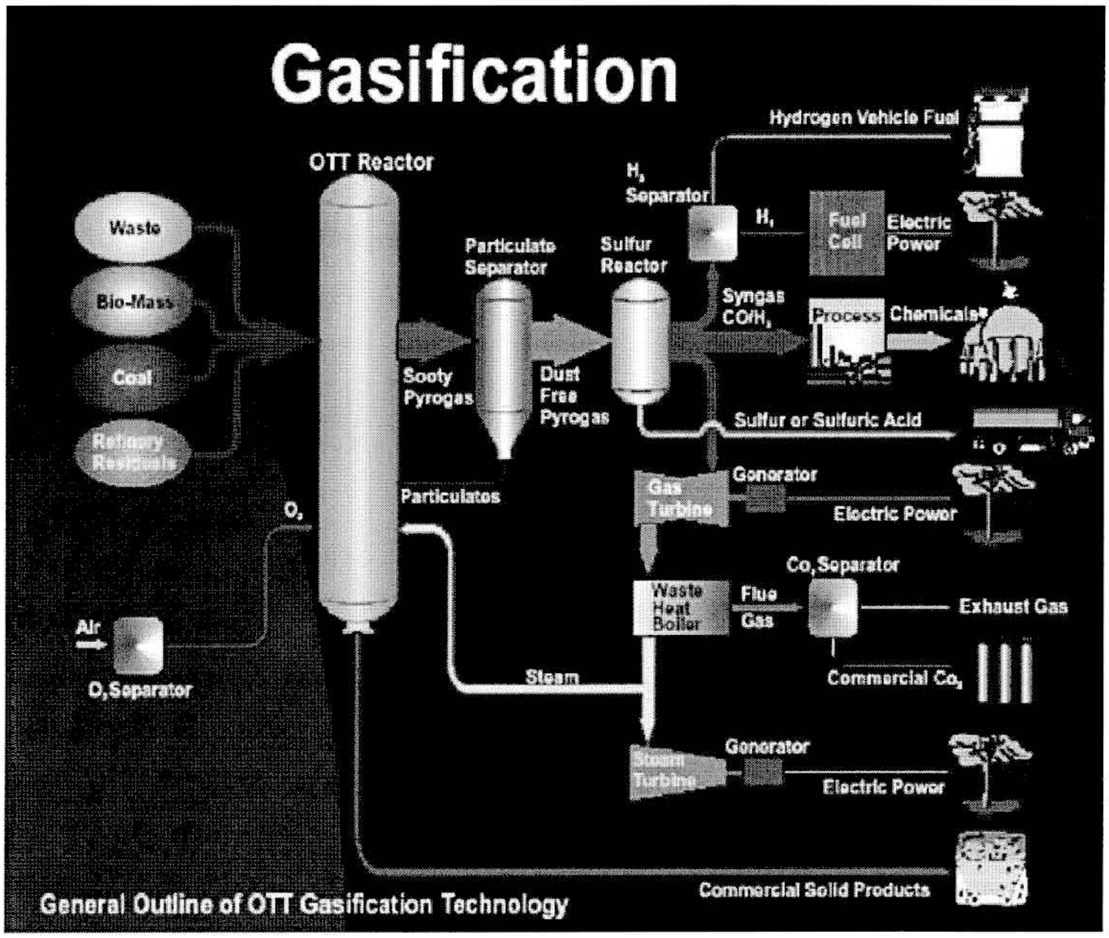


Figure 3-2: Application of gasification process in commercial sectors

3.2.4 Pyrolysis

Pyrolysis is described as the degradation of macromolecular materials or carbonaceous compounds with heat alone in the absence of oxygen. It is an endothermic reaction where heat must be supplied for the process to occur. The pyrolysis reactions are simplified into primary and secondary reactions. Primary reaction is an endothermic thermal decomposition of material to produce gas, tar (oil) and char (solid). Secondary reactions are related to the thermal degradation of volatile tars. Product yield varies and depends on operating temperature, material feed size and heating rates. Much of the present interest in pyrolysis is focused on the production of tar oil or known as the pyrolitic oil which has the potential to be used as supplementary fuel. **Figure 3-3** shows the application of pyrolysis in the bio-oil production.

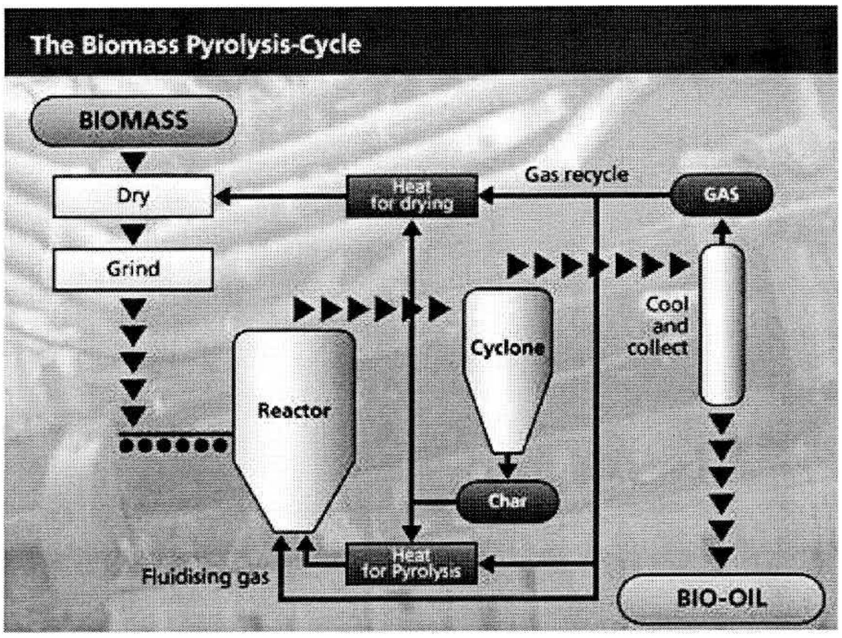


Figure 3-3: Pyrolysis of biomass for bio-oil production

3.3 Components of Incineration Process

Incinerator must be designed to accommodate different types of waste or fuels to be burned. The basic principles of combustion process are the same for all types of wastes or fuels but certain designs and configurations are most suitable for specific wastes and fuels. Three basic components of incinerator consist of fuel preparation, combustion chamber and air pollution control system. These three components are designed and constructed with limitations as what types of waste or fuels, quantity as well as its combustion efficiency.

3.3.1 Fuel preparation

Fuel preparation depends on the types of wastes or fuels to be burned. For example, municipal solid waste is burnt in a 'mass burn' incinerator where it is unprocessed except for items that are too large to go through the feeding system.

The processed municipal solid waste is known as refuse-derived fuel (RDF) and is commonly burnt in a fluidized bed and stoker type combustor. The waste is screened, sorted and separated into combustible and non-combustible materials. Shredding of combustible materials is also part of the fuel preparation to provide uniform fuel size to facilitate feeding to the combustion chamber. The RDF production line prior to combustion of RDF is shown in **Figure 3-4**.

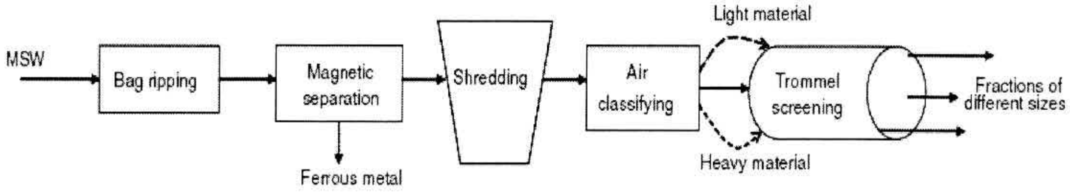


Figure 3-4: RDF production line

Liquid wastes are blended then pumped into the combustion chambers through nozzles or via specially designed atomizing burners. Wastes containing suspended particles may need to be screened to avoid clogging of small nozzle or atomizers openings. Sludges are typically fed using progressive cavity pumps and water cooled lances.

3.3.2 Combustion Chamber

The combustion chamber is where thermal destruction of waste takes place. Its design varies with waste types and capacity. Incinerators are commonly constructed with two combustion chambers. The primary chamber deals with thermal destruction of the solid waste into its ashes. It is equipped with primary air inlet, ash removal system, auxiliary fuel ports and heat transfer tubes. The operating temperature of the primary chamber is controlled by manipulating the air and feed inputs into the combustion chamber. The secondary chambers are designed to combust the 'off gas' from the primary chamber. It is where the gases emissions are fully converted to carbon dioxide and water for a complete combustion process. It is therefore equipped with an auxiliary fuel and burners to facilitate the gas combustion. It is also referred to as afterburner. The incinerator types such as moving grate, rotary kiln, step hearth and fluidized beds are referred to its primary combustion chambers. Detail description of the incinerator types are described in Section 2.1.

3.3.3 Air Pollution Controls (APC)

Air pollution controls are discussed in Module 4.

3.4 Incinerator Design

This section provides fundamental information on the design and requirement of the combustion process.

3.4.1 Residence Time

Residence time means the length of time that the combustion gas is exposed to the combustion temperature in an incinerator. It can be expressed as;

$$t = \frac{V}{q}$$ **Equation 3-1**

where $t =$ residence time
$V =$ combustion chamber volume
$q =$ gas volumetric flow rate at combustion conditions

Time and temperature affect the combustion in an incinerator. These two variables are related to each other. With a higher temperature, a shorter residence time can achieve the same degree of oxidation and vice-versa. The choice between higher temperature or longer residence time is based on the economic considerations. Increasing residence time involve using a larger combustion chamber, which results in a higher capital cost. On the other hand, raising the operating temperature increases the fuel usage which also adds to the operating costs. Balances between these two parameters are necessary for cost effective operation of the incinerator.

3.4.2 Temperature

The highest maximum achievable combustion temperature is determined by assuming the operation is carried out at an adiabatic condition (ie: no heat loss to the surroundings) and at stoichiometric condition, (AF = 1). In reality, this ideal case is difficult to achieve. However, attaining high operating temperature at stoichiometric condition is necessary to fully convert the fuel into carbon dioxide and water vapor. If air is supplied in excess of its stoichiometric point, the temperature in the combustor drops because energy is used to heat the extra combustion air. Furthermore, if too much air is supplied well above its stoichiometric, the temperature can drop below good combustion temperature and undesirable combustion products are generated as a result of incomplete combustion. A graphical presentation of the relationship between combustion temperature and air requirement of illustrated in **Figure 3-5**.

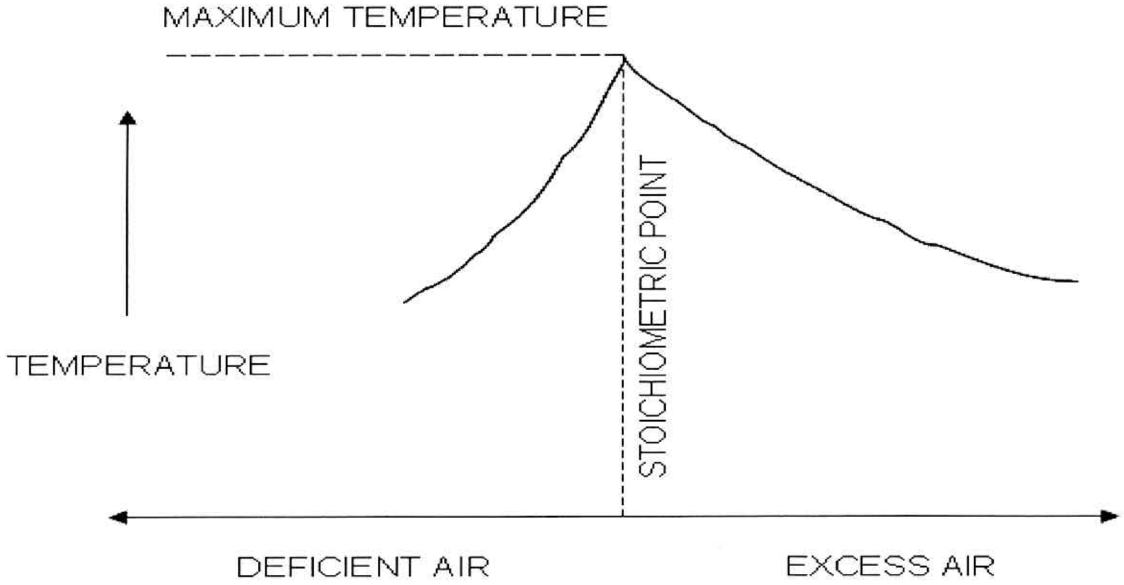


Figure 3-5: Relationship between combustion temperature and air requirement

Several processes involving waste incineration typically employ operating temperature well above 850°C as listed in **Table 3-1**.

Table 3-1: Operating furnace temperature

Type of waste	Minimum temperature, °C
Chemical waste	850
Clinical waste	1000
Municipal solid waste	850
Animal carcasses	850
Sewage sludge	850
Drum waste	850

3.4.3 Turbulence

Proper mixing of fuel and air is important in any incineration processes for achieving high combustion efficiency. In order for complete combustion to occur, every particle of fuel must come in contact with air (oxygen), otherwise the fuel might be elutriated from the combustion chamber to the stack un-reacted. Furthermore, not all of the fuels or waste gas streams are able to be in direct contact with the burner flame. If the fuel and the oxidizer are not completely mixed, a portion of the waste stream will not react at the required temperature and incomplete combustion will occur. A number of methods are available to improve mixing the air and combustion streams. Some of these include the use of refractory baffles, swirl-fired burners and baffle plates.

3.4.4 Oxygen/Air Requirement

There are several terms that are used to describe the nature of the burning process. Combustion process refers to the conversion of fuel into gaseous products and the required oxygen or air for complete combustion is known as stoichiometric combustion or theoretical combustion. Normal practice is to use the term air factor (AF) to describe the amount of air into the combustion chamber relative to its theoretical air requirement for complete combustion. If the air supply is less than the required stoichiometric air, the operation falls under gasification mode in which the product gases are carbon monoxide and hydrogen. On the other hand, if the air supply is higher than the required theoretical air for complete combustion, the process is operated at an excess air condition. The determination of theoretical air or oxygen requirement is as follows;

Let H_2O, C, H, O and S represent the weight percent of moisture, hydrogen, oxygen and sulphur in the fuel.

Then, the volume of theoretical air is (at 0^0C);

$$A_0 = (4.76X22.4\frac{L}{mol}\left(\frac{gC}{12^{g}/_{mol}} + \frac{gH}{4^{g}/_{mol}} - \frac{gO}{32^{g}/_{mol}} + \frac{gS}{32^{g}/_{mol}}\right)\text{Liter Normal})/100\text{g of fuel}$$

Equation 3-2

Assuming the air temperature is at 25^0C at room temperature and the amount of feed is 100 g/min, the amount of theoretical air required is $A_0\left(\frac{298K}{273K}\right)$ liter/min.

The volume of theoretical oxygen is calculated as follows;

$$O_2 = 22.4\frac{L}{mol}\left(\frac{gC}{12^{g}/_{mol}} + \frac{gH}{4^{g}/_{mol}} - \frac{gO}{32^{g}/_{mol}} + \frac{gS}{32^{g}/_{mol}}\right)\text{Liter Normal/100 g of fuel}$$

Equation 3-3

The weight percent of C, H, O and S are determined from the ultimate analysis of the fuel.

3.4.5 Mass and Energy Balance

In the steady state operations, the mass balance principle of the combustion process states that the inlet molar flow rate of any elemental species must be equal to the total molar flow rate of that particular element in the outlet, which may appear in one or more flue gas species. An inlet stream is considered to be consisted of moisture (H_2O), combustible substances and noncombustible (ash) materials. In the mass balance calculations, the moisture and noncombustible materials are considered to pass through the unit with only physical changes, i.e., temperature changes and the vaporization of water. For the combustible substances, the elemental species commonly considered are carbon (C), hydrogen (H), chlorine (Cl), sulphur (S), oxygen (O) and nitrogen (N). The assumptions in determining the outlet species from the inlet combustible substances are as follows;

Carbon element. All the incoming carbon (C) is either converted to carbon dioxide (CO_2) as shown in **Equation 3-4** or remains unburned and exits as solid elemental carbon. Note that the conversion of carbon to carbon monoxide (CO) is generally not considered in mass balance because carbon monoxide is not expected to be present in any significant amount in a well designed and well operated combustion system.

$$C + O_2 \rightarrow CO_2$$ **Equation 3-4**

Hydrogen element. All the incoming hydrogen will either react with chlorine to form hydrochloric acid (HCl) or converted to water (H_2O) according to **Equation 3-5** and **Equation 3-6**;

$$H + Cl \rightarrow HCl$$ **Equation 3-5**

$$2H + \frac{1}{2}O_2 \rightarrow H_2O$$ **Equation 3-6**

Chlorine element. Essentially all the incoming chlorine (Cl) is converted to hydrochloric acid (HCl).

Sulphur element. Essentially all of the incoming sulphur (S) is converted to sulphur dioxide (SO_2) according to **Equation 3-7**;

$$S + O_2 \rightarrow SO_2$$ **Equation 3-7**

Oxygen element. All the incoming oxygen, including that in inlet combustible materials and that from the air or oxygen supply, will be in either carbon dioxide (CO_2), water (H_2O), sulphur dioxide (SO_2) or oxygen gas (O_2).

Nitrogen element. All the incoming nitrogen, including that in the inlet combustible materials and that from air supply, will be in nitrogen gas (N_2). Note that the formation of nitrogen oxides (NO_x) is generally small amounts and is not considered in mass balance.

Details examples of the mass balance calculations in the combustion system are provided in the tutorial sessions.

The energy balance principle for combustion system states that under steady state operations, the difference in total energy content between the outlet and inlet streams must be equal to the amount of heat transfer and is expressed as;

$$Q = (H_{total})_{outlet} - (H_{total})_{inlet}$$ **Equation 3-8**

Note that the $(H_{total})_{outlet}$ is generally less than $(H_{total})_{inlet}$ in combustion processes and therefore the amount of heat transfer (Q) appearing in the equation (3.8) is always negative, indicating that energy is transferring out of the combustion process. This heat transfer can be in the forms of energy recovery through generating useful steam or energy lost to the surroundings. Expanding **Equation 3-8** yields;

$$Q = -(HHV)_{total} + (H_{sesible})_{outlet} - (H_{sensible})_{inlet}$$ **Equation 3-9**

where $(HHV)_{total}$ is the sum of the higher heating values from all the inlet streams, $(H_{sensible})_{outlet}$ is the sum of the sensible heat from all the outlet flue gas species (plus the heat of vaporization of water) and $(H_{sensible})_{inlet}$ is the sum of the sensible heat from all the inlet streams. Examples of the energy balance calculation are provided in Section 3.4.2 on the determination of the adiabatic flame temperature and tutorial sessions.

3.4.6 Principle Organic Hazardous Constituents (POHCs)

Operators of the incinerators are requested to conduct a trial burn of the waste and measure the level of emissions on the selected number of hazardous constituents. It is impossible to measure and monitor all hazardous constituents during the trial burn and the compounds selected for the testing are called Principle Organic Hazardous Constituents (POHCs). The POHCs are selected based on the basis of their high concentration in the waste stream, their higher toxicity, environmental impact or difficulty of destruction of these hazardous constituents in an incinerators operation.

3.4.7 Products of Incomplete Combustion (PICs)

Products of incomplete combustion are produced when the combustion process has not undergone complete combustion. In incomplete combustion there is inadequate supply of oxygen for the combustion to occur completely. Under this condition, undesirable toxic combustion products may be discharged with ash or emitted with stack gas. The most common product of incomplete combustion is carbon monoxide (CO). Concentrations of CO in the stack gas generally increase with any of the poor operating conditions. Other examples of PICs that cause concern on the health effects are benzene, dioxins, furans and other hazardous organic compounds.

3.5 Thermodynamics of Incinerator

This section provides an insight of the thermodynamic of the incineration process which involves the determination of the heating values of fuels and the adiabatic condition of the combustion process.

3.5.1 Net Heating Value

Calorific values (CV) of the solid waste is defined as the number of heat units evolved when unit mass of material is completely burned and is measured in joules per gram (J/g). The energy content of any material such as solid waste is a function of many parameters, namely physical composition of the waste, moisture content and ash content. It is also used as a means to determine the quality of the fuel and a high caloric value is an indication of a high quality fuel. Municipal solid waste is a low quality fuel compared to other biomass waste such as rice husk and coffee husk. The low quality of municipal solid waste as a fuel is due to its high moisture content. High moisture content reduces the calorific values of waste. High moisture content leads to poor ignition and reduces the combustion temperature and hinders the combustion of reaction products, thus affecting the quality of combustion. Two terms are used to describe the calorific value; High Heating Value (HHV) and Low Heating Value (LHV). The HHV is also known as the gross calorific value or gross energy. It is defined as the amount of heat released by a specified quantity once it is combusted and the products have returned to a temperature of 25^0C. The HHV takes into account the latent heat of vaporization of water in the combustion products. The HHV of waste can be estimated by using the Dulong Equation;

$$HHV\ (kJ/kg) = 33801\ (C) + 144158\ [(H) - 0.125\ (O)] + 9413\ (S)$$ **Equation 3-10**

Where; (C), (H), (O) and (S) are the mass fractions of the waste (dry basis).

On the other hand, the Low Heating Value (LHV) is also known as net calorific value of a fuel. It is defined as the amount of heat released by combusting a specified quantity and the final temperature of the combustion products is above the boiling point of water (100^0C). The LHV assumes the latent heat of vaporization of water in the fuel and the reaction products is not recovered.

Therefore, to calculate a LHV of a fuel from a HHV or vice versa, the moles of water produced when a mole of fuel is burned must be determined.

Hence;

$$\text{HHV} = \text{LHV} + n\Delta \hat{H}_v\ (H_2O, 25°C)$$

The heat of vaporization of water at 25°C is;

$$\Delta \hat{H}_v\ (H_2O, 25°C) = 44.013\ \text{kJ/mol or } 2.445\ \text{MJ/kg}$$

3.5.2 Adiabatic Condition in Incinerator

When a fuel is burned, a considerable amount of energy is released. Some of this energy is transferred as heat through the combustor walls to the surroundings and the remainder raises the temperature of the reaction products. The highest achievable combustion temperature when the combustor is operating adiabatically (no heat loss to surroundings) and undergoes complete combustion (Air Factor = 1) is called Adiabatic Flame Temperature. Energy balance for combustion of fuels for adiabatic condition ($\Delta H = 0$) is as follows;

$$\Delta H = n_f \Delta \hat{H}_c + \sum_{out} n_i\ H_i(T_{ad}) - \sum_{in} n_i\ \hat{H}_i(T_{feed}) = 0$$ **Equation 3-11**

Thus;

$$\sum_{out} n_i\ \hat{H}_i(T_{ad}) = -\ n_f \Delta \hat{H}_c + \sum_{in} n_i\ \hat{H}_i(T_{feed})$$ **Equation 3-12**

where;

$\Delta \hat{H}_c$ = heat of combustion of the fuel at reference temperature 25°C

n_i = moles of the i^{th} component in the feed or product

$\hat{H}_i$ = specific enthalpy of the i^{th} component at 25°C

T_{ad} = adiabatic flame temperature, °C

Calculation of $-n_f \Delta \hat{H}_c$ **,**

$\Delta \hat{H}_c$ is evaluated at 25^0C with liquid water as a combustion product. Therefore, it is higher heating value (HHV) or total heating value or gross heating value. However, in the combustion process, water is produced in vapour state. Therefore, the net heat produced during the combustion process is the lower heating value (LHV) with the consideration of latent heat of vaporization of water. Thus, the calculation of LHV is as follows;

$$\mathrm{LHV} = \mathrm{HHV} - n\Delta H_v(H_2O, 25°C)$$ **Equation 3-13**

Where, the heat of vaporization of water, ΔH_v = 44.013 kJ/mol. To simplify the adiabatic flame calculation, the term $-n_f \Delta \hat{H}_c$ can be replaced by $-n_f LHV$. Hence;

$$-n_f \Delta \hat{H}_c = -n_f \mathrm{LHV}$$ **Equation 3-14**

Calculation of $\sum_{input} n_i \hat{H}_i (T_{feed})$,

The equation is evaluated from the reference state at 25°C for fuel (waste), therefore, $\hat{H}_{fuel(25^oC)} = 0$ kJ/mol and for example air at the operating combustor temperature of 800°C, thus $\hat{H}_{air(800^oC)} = 24.10$ kJ/mol.

Calculation of $\sum_{output} n_i \hat{H}_i (T_{ad})$, The equation is evaluated and expanded as follows;

$$\sum_{\text{output}} n_i \hat{H}_i (T_{ad}) = n_{H_2O(v)} (\Delta H_v)_{H_2O} + \int_{25°C}^{\hat{T}_{ad}} (\sum n_i Cp_i)\, dT$$ **Equation 3-15**

where liquid water must first vaporize at 25°C. The heat of vaporization of water at 25°C is 44.013 kJ/mol. The heat capacities of the product gases in kJ/mol°C in terms of T (°C) are;

$$(Cp)_{co_2} = 0.03611 + 4.233 \text{ x } 10^{-5} T - 2.887 \text{ x } 10^{-8} T^2 + 7.464 \text{ x } 10^{-12}\, T^3$$ **Equation 3-16**

$$(Cp)_{H_2O_{(g)}} = 0.03346 + 0.688 \text{ x } 10^{-5} T + 0.7604 \text{ x } 10^{-8} T^2 - 3.593 \text{ x } 10^{-12}\, T^3$$ **Equation 3-17**

$$(Cp)_{O_2} = 0.02910 + 1.158 \text{ x } 10^{-5} T \;\; 0.6076 \text{ x } 10^{-8} T^2 - 1.311 \text{ x } 10^{-12}\, T^3$$ **Equation 3-18**

$$(Cp)_{N_2} = 0.02900 + 0.2199 \text{ x } 10^{-5} T + 0.5723 \text{ x } 10^{-8} T^2 - 2.871 \text{ x } 10^{-12}\, T^3$$ **Equation 3-19**

The first law of thermodynamic stated that in adiabatic process, $\Delta H = 0$. Therefore, the general equation yields

$$\Delta H = n_f \Delta \hat{H}_c + \sum_{\text{output}} n_i \hat{H}_i (T_{feed}) - \sum_{\text{input}} n_i \hat{H}_i (T_{ad}) = 0$$ **Equation 3-20**

The adiabatic flame temperature is therefore determined through trial and error process.

3.6 Heat Transfer

This section provides information on the process involves in the transfer of heat from the furnace to water in boiler operation for steam production. The utilization of heat conversion from waste to useful energy is also pointed out and finally the aspect of heat loss minimization via the use of refractory and insulation materials is highlighted.

3.6.1 Maximizing Heat Transfer

A boiler is a closed vessel in which water under pressure is transformed into steam by the application of heat. The primary function of a boiler is to maximize the transfer of heat from the furnace or flue gas to the water to produce steam for electricity generation. Two most commonly boiler designs are fire tube boilers and water tube boilers.

Fire tube boilers – It can be described as a water-filled vessel with tubes running through it. As the flue gas passes through the tubes, the hot gases heat the tubes and then heat the water to produce steam. Diagram of a fire tube boiler is illustrated in **Figure 3-6**.

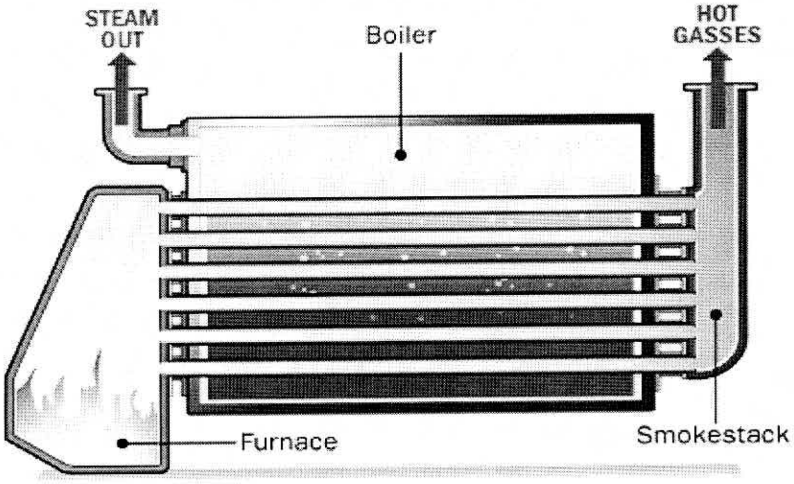


Figure 3-6: Fire tube boiler

Water tube boiler - The design of the boiler is that the water is circulated through the tubes with the hot combustion gases passing over the outside surfaces of the tubes. Diagram of the water tube boiler is shown in **Figure 3-7**.

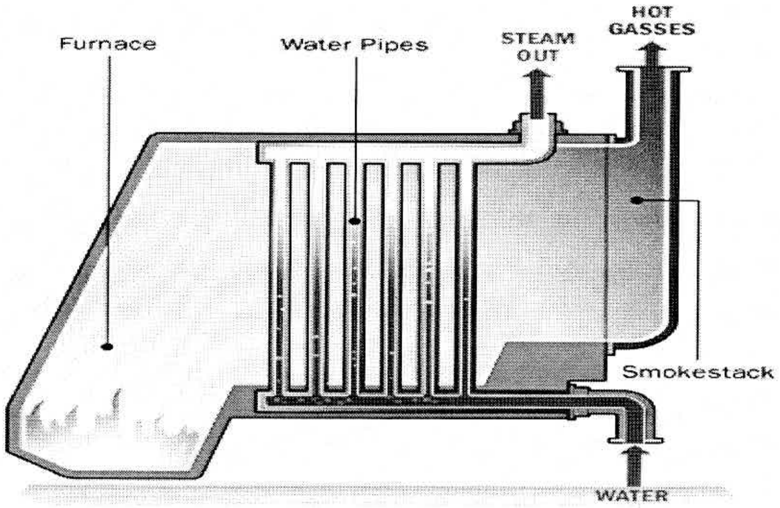


Figure 3-7: Water tube boiler

Boiler maintenance is important as several issues associated with erosion, corrosion, fouling and deposition are the major problems in boiler operation.

Erosion in boilers is due to the impingement of solid particles and hot gases moving in high velocity acting on the surface of the tubes. It normally occurs in a water tube boiler such as reported in most fluidized bed combustor operation.

Corrosion happens on the outer and inner surface of the tubes for both types of boilers. Internal corrosion in the pressurized part of the boiler is due to water chemistry such as corrosion fatigue, a leading material failure in many boilers. External corrosion is also known as fireside corrosion where it receives direct impact of fuel combustion.

Fouling and deposit formation happens when some ash from the combustion is carried out of the furnace with the flue gases. Part of the ash deposited inside the furnace can melt and cause slagging. If the ash is deposited in the gas duct downstream of the furnace, it is called fouling and the ash does not melt. Deposit formation or soots on the boiler tubes is one of the causes of fireside corrosion.

3.6.2 Utilization of Heat Exchange

The waste can be converted into useful forms of energy using three most commonly used thermal treatment methods namely combustion, gasification and pyrolysis. Its utilization of heat exchange from waste to energy is as follows;

(i) By direct combustion to provide heat for use of heating, for steam production and hence electricity generation through steam turbine operation
(ii) By gasification to provide a fuel gas for heat or turbine (gas turbine) for electricity generation
(iii) By pyrolysis to provide a liquid fuel that can substitute for fuel oil and easily stored and transported

Several power production plants and domestic incinerators are in service with different types of waste such as municipal solid waste, clinical waste, biomass waste and chemical waste.

3.6.3 Minimization of Heat Loss

In order to minimize heat loss in the combustor operation, proper design and selection of inner linings are very important. Refractory and insulation materials are used as inner linings. Both provides an excellent means of reducing heat loss and generally serves two purposes:

(i) refractory material gives protection against erosion and abrasion due to hot abrasive particles and gases moving at high velocities
(ii) insulation material is used to protect against high temperature and minimize heat loss to the surroundings

There are a wide variety of refractory and insulation products. Their significant properties of this material include;

(i) Abrasive - able to withstand physical contact with the gaseous, liquid or solid materials on the hot face

(ii) Resistance – able to withstand corrosion in which some chemical reactions or processes that might destroy the refractory bond or the chemical integrity of the insulation

(iii) Insulating value – able to provide resistance to the flow of heat

(iv) Mechanical shock resistance – able to withstand handling and shipping without damage and structural strength provided by load testing

(v) Strength – able to maintain strength (modulus of rupture) under high temperature conditions

(vi) Spalling - able to withstand a deterioration of the surface of the refractory by flaking caused by abrasion, corrosion or mechanical and thermal shock

(vii) Resistance to the operating condition – able to withstand the operational condition in an oxidizing and reducing atmosphere. For example, reducing atmosphere (deficient in oxygen will tend to degrade material containing iron or silicon components.

There are two commonly types of refractory materials and insulators namely castables (refractory concrete) and firebrick.

(i) castables – classified as dense and lightweight (insulating). Dense castable have excellent mechanical strength and low permeability. Their insulating properties, however, are relatively poor but it offers good resistance in wet condition such as quencher linings. Typical specific weight is over 1600 kg/m^3. Lightweight castables are excellent insulators but has limited service temperature of below 1650°C.

(ii) firebrick – classified as conventional firebrick and insulating firebrick. Conventional firebrick is a dense brick with specific weight of over 1600 kg/m^3 and has relatively poor insulating qualities. It contains up to 44% alumina and normally firebrick is placed in direct contact with the hot gas stream. Insulating firebrick is a lightweight porous brick with specific weight less than 800 kg/m^3. It has low structural strength than conventional firebrick and due to its porosity and soft material not suitable to erosive hot gas stream.

3.7 Computational Fluid Dynamic (CFD)

The computational fluid dynamics is the numerical solutions of equations of continuity and momentum. The continuity equation refers to the mass balance (mass conservation) principle applied to a control volume whilst the momentum equation or Navier-Stokes was use to evaluate the transport and energy conservations. The CFD software can be use to predict the gas flow, turbulence, temperature and other behaviors of gas-solid and gas conditions under different load conditions. Example of the CFD software is FLUENT and is used extensively in predicting the behavior of gas and solid in fluidized bed hydrodynamic studies. **Figure 3-8** and **Figure 3-9** illustrate the simulation study on the residence time of the combustion gas in the mass burn incinerator and the hydrodynamic of gas-solid in a fluidized bed.

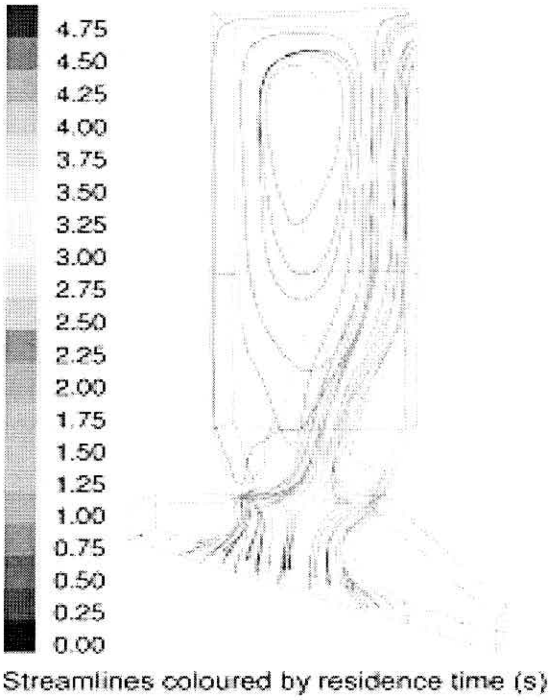


Figure 3-8: FLUENT simulation on gas residence time in a mass burn incinerator

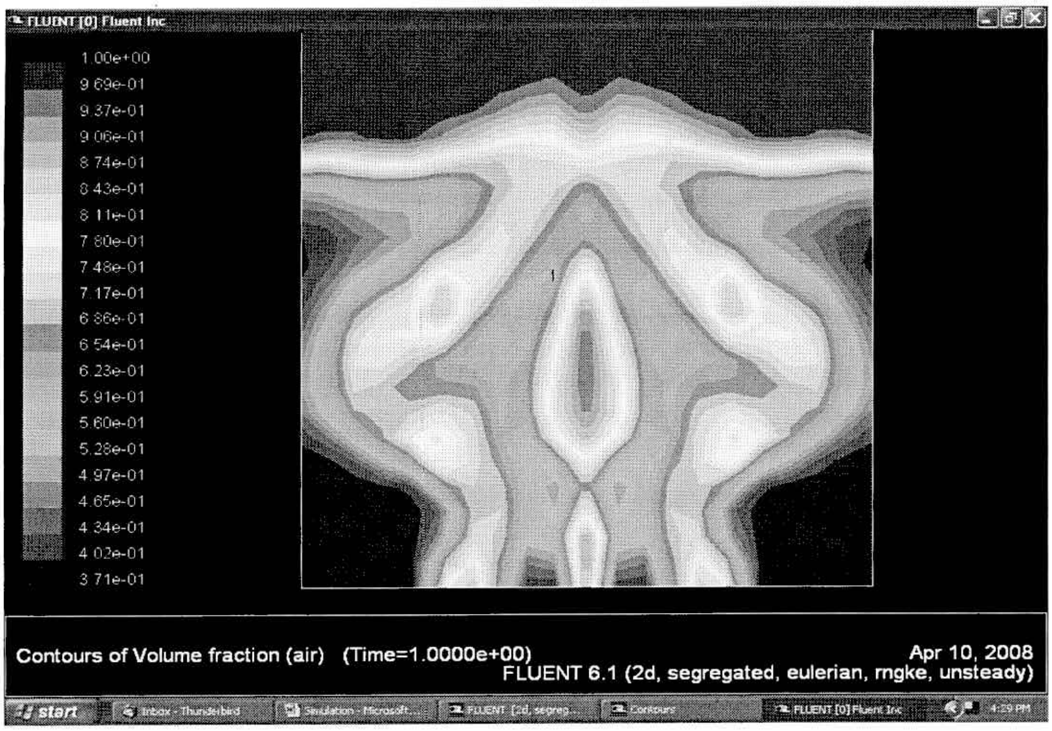


Figure 3-9: FLUENT simulation on gas-solid fluidization

MODULE 4

ENVIRONMENTAL IMPACTS AND POLLUTION CONTROL

MODULE 4

ENVIRONMENTAL IMPACTS AND POLLUTION CONTROL

LEARNING OUTCOMES:

- ✓ Describe the formation and control of pollutants from incineration process
- ✓ Able to identify the air pollution control equipment and its function
- ✓ Describe the air pollution control systems used in incinerator plant
- ✓ Describe the design of stack height

4.1 Source of pollutant emissions

Sources of pollutant emissions from incineration process are as follow:

a) Combustion process
b) Waste (fuel) composition
c) Incinerator operation

4.2 Formation and control of pollutants

4.2.1 Products of incomplete combustion (PIC)

There are three types of PIC:

- Total organic carbon (TOC)
- Carbon monoxide (CO)
- Dioxin/furan

All organic carbon produced from combustion process are referred as TOC. TOC can be found in bottom ash, filter dust and flue gas. Examples of TOC are shown in **Table 4-1**.

Table 4-1: Emission of TOC from combustion process

Volatile organic compound (VOC)	**Semi volatile organic compound**
Benzene	Naphthalene
Toluene	Phenol
Carbon tetrachloride	Bis (2-ethylhexy) phthalate
Chloroform	Diethylphtalate
Methylene chloride	Butylbenzylphtalate
Trichloroethylene	Dibutylphtalate
Petrachloroethylene	
1,1,1-Trichloroethane	
Chlorobenzene	

Insufficient air during combustion and excessively low temperature (below 800°C) results in formation of CO. CO can be used as a measure of combustion quality. If CO is very low, then VOC is expected to be low due to destruction kinetic of VOC to form CO. The mechanism of VOC conversion to CO and CO_2 is as follows:

$$\text{VOC} \xrightarrow[\text{fast}]{} \text{CO} \xrightarrow[\text{slow}]{} \text{CO}_2$$

The main PICs generated from combustion process are dioxins and furans, tar and soot particles.

PICs can be controlled by proper incinerator operation in terms of temperature, residence time and oxygen as discussed in Module 3.

4.2.2 Dioxins

Dioxins are classified into two types such as follow:

- Solid form, i.e. particulate-bound dioxins/furans
- Vapour form

There are three sources of dioxins formation:

- Waste (fuel)
- Incomplete combustion
- De-novo synthesis

Dioxins may form during combustion when the fuel already carries dioxin compound. However, dioxins levels in most wastes are relatively low. Even when they are significant, a well designed furnace will effectively destroy them and most organic precursors.

As mentioned in Section 4.2.1, incomplete combustion results in dioxins formation. However, too high excess air also encourages dioxins formation by releasing Cl_2. Secondary air is often added more than is needed for oxygen requirements in order to induce turbulence. However this can be avoided by using flue gas recirculation (FGR) which replaces the air with CO_2. FGR can reduce dioxins formation by 25-50%.

Dioxins formation also occurs during flue gas cooling between 450 to 200°C which is termed as de novo synthesis. Therefore, cooling should take place as rapidly as possible. Slow cool down rate of the gases results in increased scope for the formation of dioxins.

Boiler is the place where most dioxins form by de novo synthesis. This is because boiler deposits contain subtances which catalytically enhance dioxin formation with the presence of carbon, oxygen and chlorine. Hence, minimising boiler deposits is vital. It can be achieved by the following methods:

- Design features to maintain critical surface temperature below the sticking temperature. This includes not only the arrangement of cooling surfaces but also avoiding peak combustion temperatures by good waste mixing, uniform waste feed, and good primary and secondary air control.
- Additives to prevent sodium and potassium depositing.
- Cleaning by steam or compressed air soot blowing.

Effective destruction of dioxins in the waste can be achieved by proper incinerator operation in terms of time, temperature, residence time and oxygen as discussed in Module 3. In addition, dioxins can also be controlled using the following control methods:

a) By injection of activated carbon upstream of bag filter
b) Selective non-catalytic reduction (SNCR)
c) De-NOx treatment system may also reduce dioxins/furans

4.2.3 Acid gases

Waste may include compounds containing chlorine, fluorine, sulfur, nitrogen and other elements which may result in the generation of toxic or corrosive gases. Plastic waste containing chlorine and fluorine results in formation of acid gases such as hydrogen chloride, HCl and hydrogen fluoride, HF. Sulfur dioxide (SO_2) is formed when waste containing sulfur is burned.

Acid gases are normally controlled by neutralization using alkaline sorbent such as lime or sodium bicarbonate (discussed below).

4.2.4 Particulate matter

The gas stream whilst passing through the waste bed, may extract ash, dust, and char, carrying them into the flue gas stream to produce particulates. Metals and salt may evaporate in the furnace to condense eventually in the colder parts of the flues and generate an aerosol of submicron particles.

Particulate matter is controlled by dust removal devices such as cyclone, electrostatic precipitator (ESP) and bag filter (discussed below).

4.2.5 Heavy metals

Heavy metal pollutants such as mercury (Hg), cadmium (Cd) and lead (Pb) originate from the waste itself. Combustion process will change the form of metal fraction in waste streams but it will not destroy the metals. As a result, metals are expected to emerge from the combustion zone essentially in the same quantity as the input.

During combustion process, reduced temperature in the primary chamber can reduce the rate of metal evaporation. Gasification which runs at temperature lower than 600°C produces less metal emission than excess air combustion ($T > 800°C$).

Metals in particulate form are removed by bag filter. Meanwhile, metals in vapor form (i.e. mainly mercury) are first adsorbed in activated carbon and then removed by bag filter.

4.2.6 Nitrogen oxides (NOx)

There are two types of NOx; fuel NOx and thermal NOx. Fuel NOx is formed during combustion process from nitrogen in the waste meanwhile thermal NOx is by direct combination of oxygen and nitrogen at high temperature.

Control of fuel NOx:

- Total excess air rates
- Ratio of primary to secondary air

Control of thermal NOx:

- Lowering combustion temperature
- Minimising oxygen in the flame area

NOx can also be controlled using low NOx burner. Low NOx burners are designed to control fuel and air mixing at each burner in order to create larger and more branched flames. Peak flame temperature is thereby reduced, and results in less NOx formation.

4.2.7 Solid outputs

Incineration process produces two type solid outputs such as follow:

a) Bottom ash
b) Fly ash

Bottom ash is residues that remain after combustion. Bottom ash commonly constitutes 90% of solid output from incinerator. Dust or particulate matter that is removed from exhaust flue gases is termed as fly ash and makes up another 10% of solid output. Typical incinerators in general produce about 10% bottom ash and 3% fly ash from waste burned. For example, 100 tonnes/day incinerator burning solid waste typically produces 10 tonnes/day of bottom ash and 3 tonnes/day of fly ash. However, the exact quantities of solid outputs from incinerator depend on the following factors:

- The quantity of waste burned
- The composition of the waste burned

- Any recycling schemes which might reduce the quantities of glass or metals in the input waste
- The design and operation of plant

Typical constituents of ash are shown in **Table 4-2**. Fly ash from scheduled waste (i.e. clinical waste) and non-scheduled waste incinerator is rendered as scheduled waste which requires final diposal at Kualiti Alam. As for bottom ash, only the one generated from scheduled waste incinerator falls under scheduled waste. Bottom ash from non-scheduled waste incinerator can be re-used for puposes as shown in **Table 4-3**.

Table 4-2: Typical constituents of ash

Silica (SiO_2)	Potassium oxide (K_2O)
Alumina ($Al2O_3$)	Titanium dioxide (TiO_2)
Iron oxides	Zinc oxide (ZnO)
Magnesia (MgO)	Cadmium
Quicklime (CaO)	Lead
Sodium oxide (Na_2O)	Mercury
Silica (SiO_2)	Potassium oxide (K_2O)
Alumina (Al_2O_3)	Titanium dioxide (TiO_2)

Table 4-3: Uses of incineration ash

Construction materials	• Cement production • Concrete • Ceramics • Glass and glass-ceramic
Geotechnical	• Road pavement • Embankment
Agriculture	• Soil amendment
Others	• Sorbent • Sludge conditioning

4.3 Effects of pollutants emissions

Pollutants emissions from incineration process can cause harmful effects to human health as well as the environment.

a) Human health

Pollutants such as particulate matter, organic carbon, heavy metals and dioxins and furans are identified as capable to affect human health as shown in **Table 4-4**.

Table 4-4: Effects of incinerator pollutant to human health

Pollutant	**Health effect**
Particulate matter	Pulmonary disease, heart disease and pneumonia
Organic carbon	Non biodegradable, accumulate in fatty tissues and several of them have been linked to increased risk of cancer.
Heavy metals	Exert a range of chronic and acute health effects including carcinogenic, neurological, hepatic and renal.
Dioxins	Adverse effects upon reproduction and development, suppression of the immune system, chloracne (a sevre acne-like condition that sometimes persist for many years, and cancer.

b) Environment

Acid gases that form from incineration process may react with water or water vapor to produce acids such as sulphuric acid, hydrochloric acid and nitric acid. Emission of acid gases to atmosphere causes reaction with water molecule which then results in acid rain (**Figure 4-1**). Acid rain is acidic (low pH) and poses harmful effects on plants, aquatic animals and infrastructure.

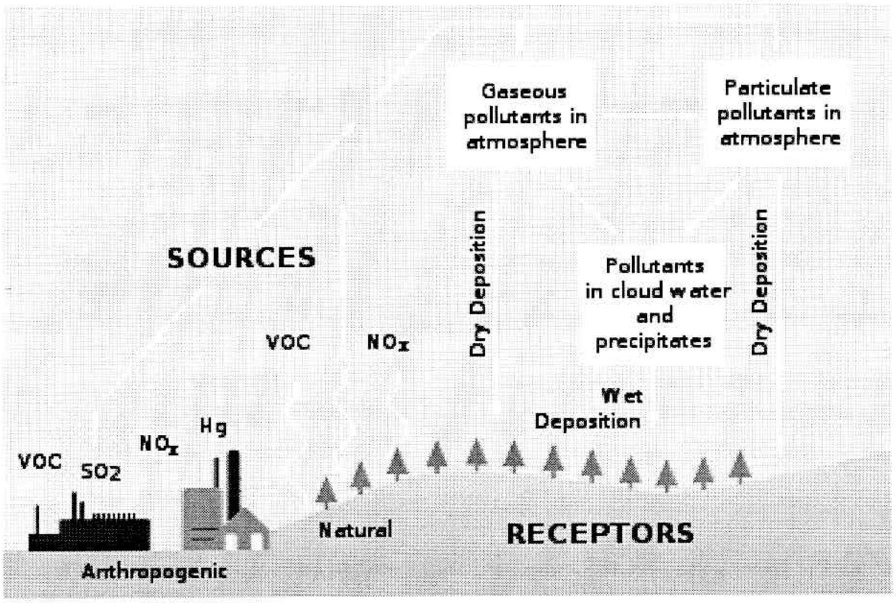


Figure 4-1: Acid rain phenomena

4.4 Equipment for air pollution control (APC)

Flue gas generated from incineration process contains harmful contaminants which need to be removed before the flue gas can be discharged into environment. The flue gas out of primary and secondary chamber is cleaned by several air pollution control equipment before releasing it to the atmosphere. The commonly used equipment is cyclone, wet scrubber, bag-house filter and electrostatic precipitator (ESP).

Cyclones – cyclones are used to separate particulates from the flue gas stream. Collection efficiency can be at least 90% for particles bigger than $10\mu m$ but the efficiency is low for finer particles. Cyclone separators operate based on centrifugal force to separate particulates from the gas stream and they are collected at the bottom of the cyclone. **Figure 4-2** shows the diagram of a cyclone.

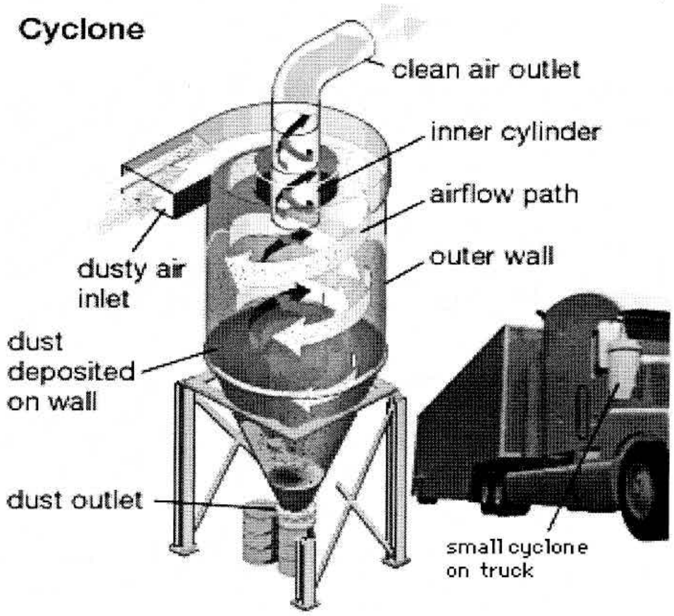


Figure 4-2: Diagram of a cyclone

Wet scrubber – This equipment traps suspended particles by direct contact with a spray of water or other liquid. In effect, a scrubber washes the particulates out of the dirty air stream as they collide with and are entrained by the countless tiny droplets in the spray. Several configurations of wet scrubbers are in use. In a spray-tower scrubber, an upward-flowing air stream is washed by water sprayed downward from a series of nozzles. The water is re-circulated after it is sufficiently cleaned to prevent clogging of the nozzles. Spray-tower scrubbers can remove 90 percent of particulates larger than about 8 mm (0.0003 inch). **Figure 4-3** and **Figure 4-4** shows the diagram of the wet scrubber and actual equipment installation for air pollution control.

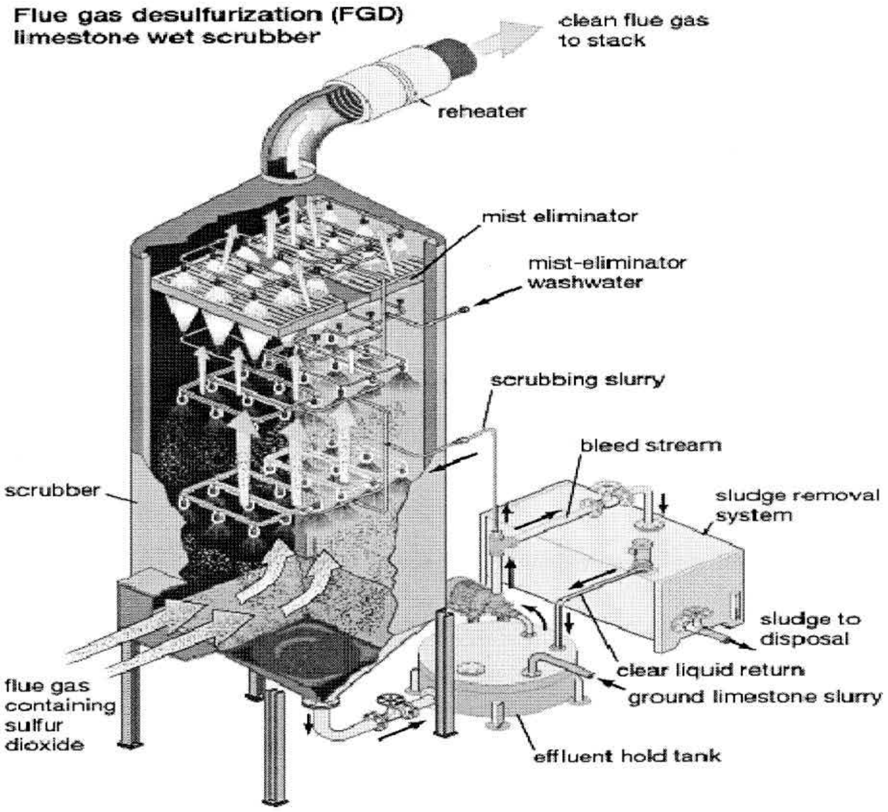


Figure 4-3: Diagram of a wet scrubber

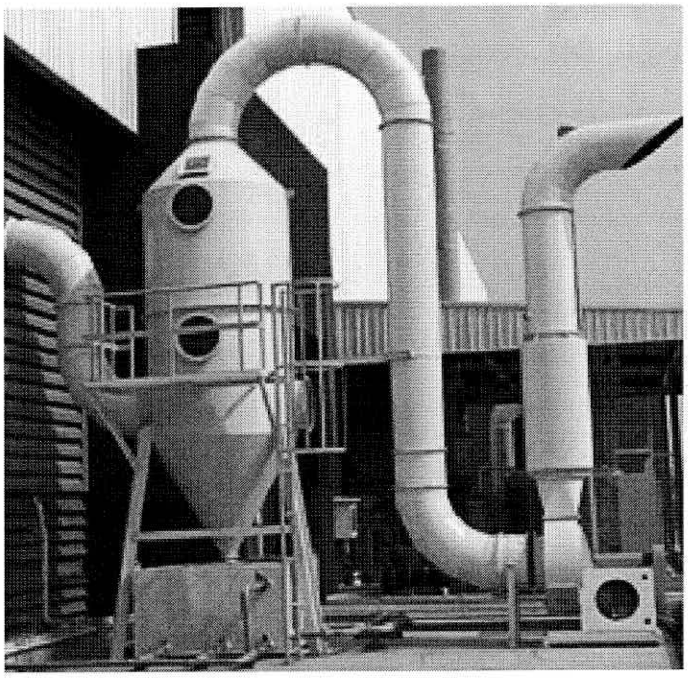


Figure 4-4: Actual wet scrubber installation

Baghouse Filter – capable of removing suspended particulates. A typical baghouse comprises an array of long, narrow bags, each about 25 cm (10 inches) in diameter that is suspended upside down in a large enclosure. Dust-laden air is blown upward through the bottom of the enclosure by fans. Particulates are trapped inside the filter bags, while the clean air passes through the fabric and exits at the top of the baghouse. A fabric-filter dust collector can remove very nearly 100 percent of particles as small as 1 mm (0.00004 inch) and a significant fraction of particles as small as 0.01 mm (0.0000004 inch). Fabric filters, however, offer relatively high resistance to airflow, and they are expensive to operate and maintain. Additionally, to prolong the useful life of the filter fabric, the air to be cleaned must be cooled (usually below 300°C) before it is passed through the unit; cooling coils needed for this purpose add to the expense. Certain filter fabrics, e.g., those made of ceramic or mineral materials can operate at higher temperatures. The bags are cleaned by mechanical shakers or by reversing the flow of air and the loosened particulates are collected and removed for disposal. **Figure 4-5** and **Figure 4-6** shows the diagram and the actual installation of the baghouse filter.

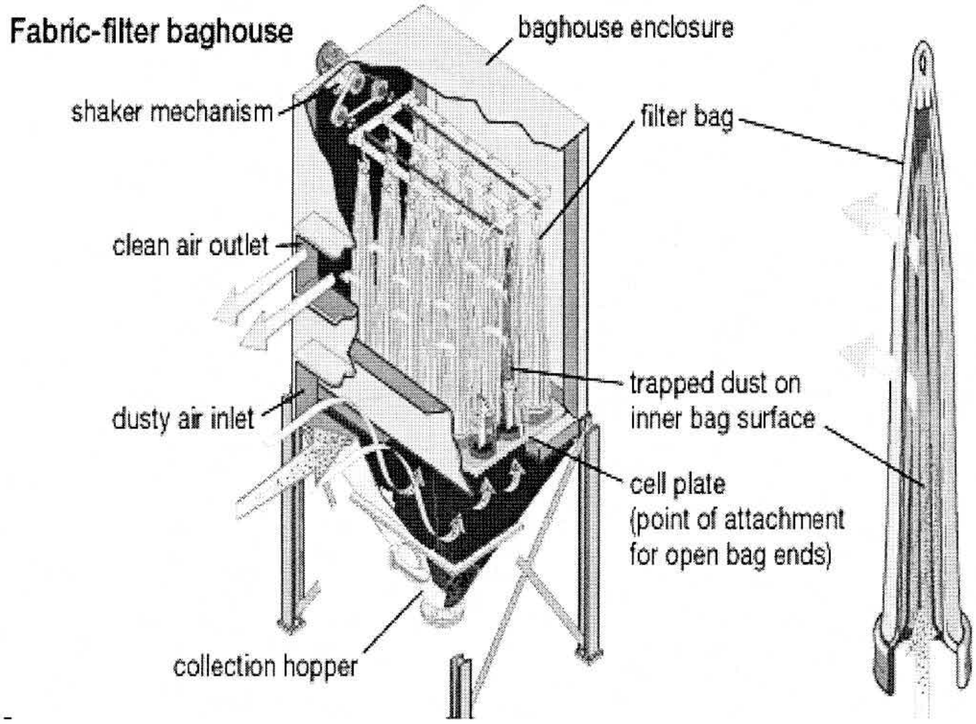


Figure 4-5: Diagram of a baghouse filter

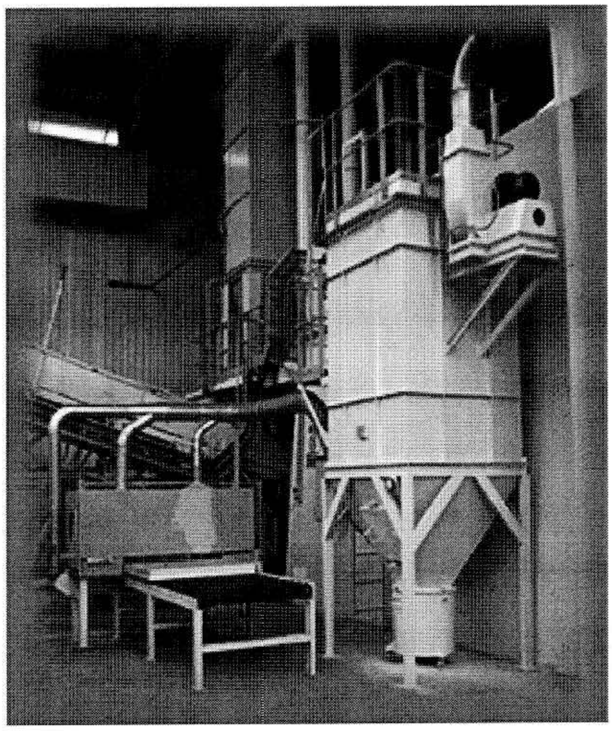


Figure 4-6: Actual baghouse filter installation

Electrostatic Precipitator (ESP) – This device is mainly used for separation of particles less than $1\mu m$. Overall particulate removal efficiency is often well over 99% and the performance of the ESP depends on the gas velocity and the electrical resistivity of the particles. The basic components of an ESP are the discharge electrode (corona), collection electrode (plates) and high voltage equipment. High voltage is applied to the discharge electrode which generates the electric field between the discharge and the collection electrodes. As the flue gas flows through the ESP, the particulates are charged with negative ions due to the influence of the discharge electrode. The negatively charged particulates then migrate towards the positively charged collecting plates and form a dust layer. Dust accumulated on the surface of the plates is dislodged by rapping and collected in hoppers at the bottom of the ESP. Diagram of the ESP is shown in **Figure 4-7**.

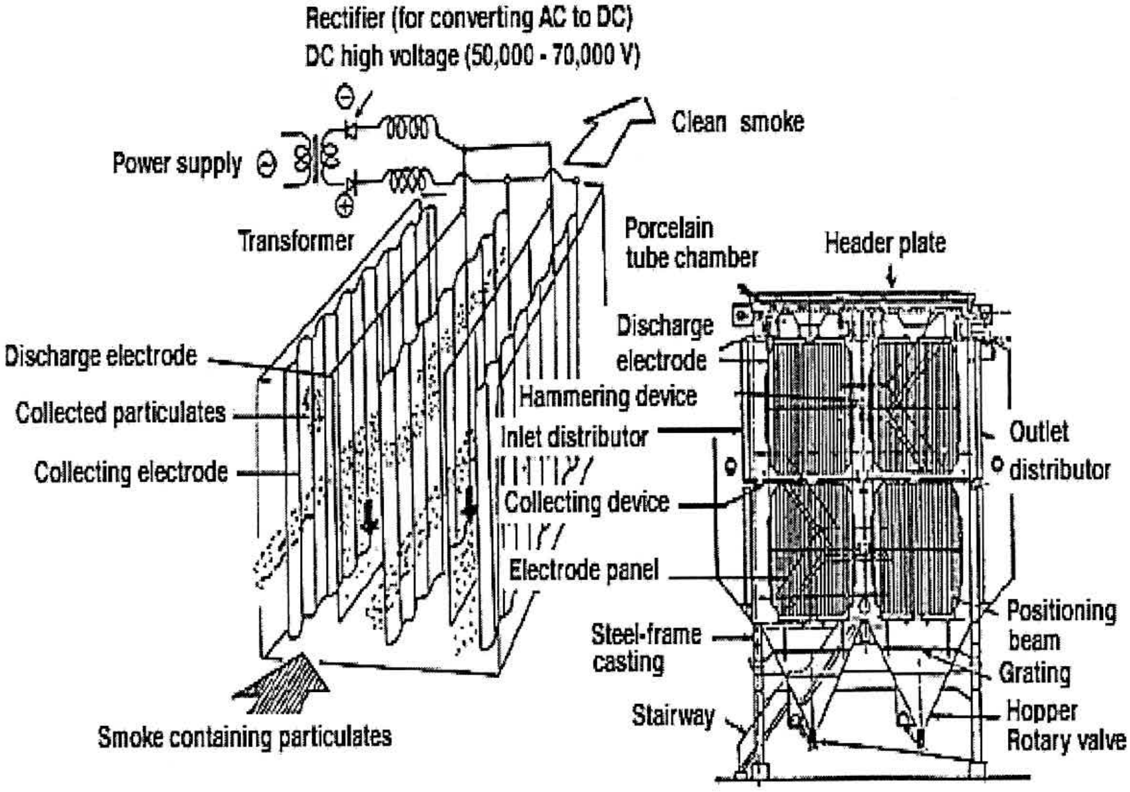


Figure 4-7: Electrostatic Precipitator

4.4.1 Comparison of air pollution control for dust removal

Advantages of the air pollution control equipment in removing dust are listed in **Table 4-5**.

Table 4-5: Achievable emission concentration of dust and advantages of dust removal device

Dust removal device	**Emission concentrations (mg/m^3) that can be achieved**	**Advantages**
Cyclone Multi cyclones	200 – 300 100 -150	- Robust, relatively simple and reliable - Appropriate only as pre-dusting device
Dry ESP	< 25	- Relatively low power requirement - Ability to accommodate gas temperature in the range of 150-350°C
Wet ESP	< 5	- Able to reach low emission concentration
Bag filter	< 5	- The layer of residue acts as an additional filter and as an adsorption reactor

Bag filters are normally more efficient for particulate metal removal than ESPs and offer additional control of SO_2 on the reactive bag dust cake. They also require slightly less space and have generally a lower capital cost than ESPs. However, bag filters have higher running costs than ESPs and cannot sustain high flue gas temperatures. They can also exhibit blinding or wetting problems and need by-pass and special heating facilities in the event of breakdown.

4.4.2 Air pollution control (APC) system

For incinerator plant, one unit of air pollution control is not sufficient to control all pollutants generated from incineration process. Typically, a combination or hybrid system is required to ensure effective control of air pollutants from incinerator. The most common systems used in incinerator plant are as follow:

- Wet scrubber
- Dry scrbber

4.4.2.1 Wet scrubber

Wet scrubber involves spraying of an aqueous solution of alkaline sorbent material (i.e. lime) into flue gas. It removes acid gases and particulate matter through absorption and chemical reaction with scrubbing liquor. The diagram of wet scrubber system is shown in **Figure 4-8**.

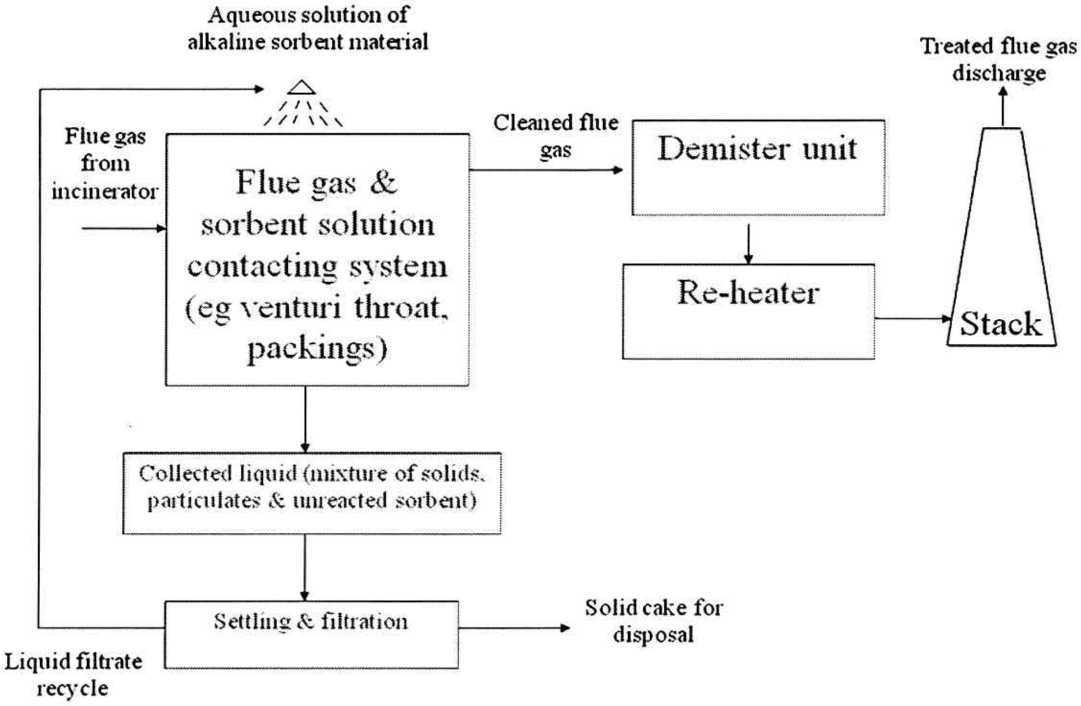


Figure 4-8: Schematic diagram of wet scrubber system

4.4.2.2 Dry scrubber

Dry scrubber generally involves spraying of dry sorbent material (i.e. lime or sodium bicarbonate into flue gas to remove acid gases by a combination of adsorption and neutralisation. Flue gas is then passed through filter to remove sorbent materials and particulates. Solids are collected at bottom of filter unit and flue gas is discharged into atmosphere through stack. The dry scrubber system is shown in **Figure 4-9**. Recently most of the incinerator plants utilize dry scrubber. Inherent disadvantages of wet scrubber:

- Corrosion
- Wet sludge
- White smoke

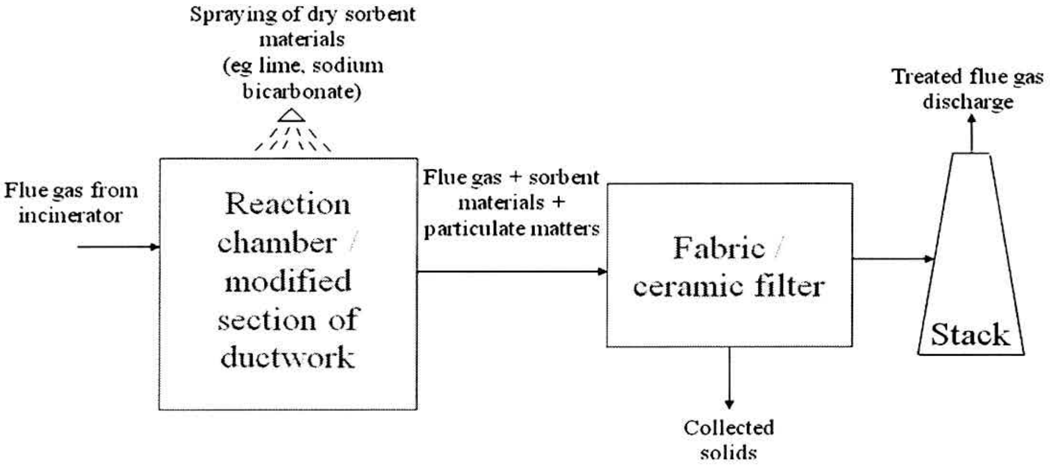


Figure 4-9: Schematic diagram of dry scrubber system

4.5 Stack

Stack is a vertical pipe, channel or similar structure through which flue gases are exhausted to the atmosphere. The purpose of stack is to disperse the exhaust pollutants over a greater area and thereby reduce the concentration of the pollutants to the levels required by environmental regulation. In other words, stack aims to mitigate residual impact of air pollution from incinerator that may arise even after treatment of flue gas using air pollution control system.

4.5.1 Stack height

Design of stack at sufficient height is imperative so that atmospheric dispersion will reduce the ground level concentrations to allowable values. Generally, the inside diameter of the stack decreases with increasing stack height. Factors that influence the design of stack are as follow:

a) The area of the source
b) The discharge velocity of the effluent
c) The required effective discharge height
d) The minimum dependable horizontal wind speed
e) The expected lapse rate in the vicinity of the emisssion point

In determining sufficient stack height, the effect of plume downwash should be taken into consideration. As air blows past a structure, a low pressure region forms behind the structure resulting in recirculating eddies and wake formation. In addition, if the structure is large, disturbances in the flow system are experienced above and on either side of the structure. Typical disturbances from a building and from the stack itself are illustrated in **Figure 4-10**.

The following rules can be used to avoid plume downwash behind a stack:

- Stack height must be at least 2.5 times the height of the highest building near the stack.
- Stack diameter must be small enough to ensure that the stack exit velocity is greater than 1.5 times the maximum expected sustained wind speed at stack height. The capital cost of the stack will be decreased by decreasing the stack diameter. However, pressure drop in the stack will increase as the square of the gas velocity, thus increasing fan power cost.

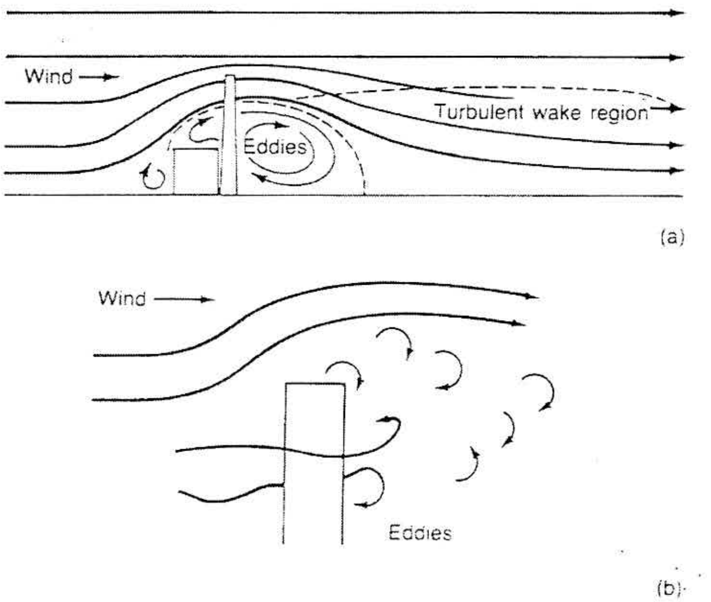


Figure 4-10: Typical flow disturbances owing to (a) a building and (b) a stack

The calculation method to determine chimney height is shown in Memorandum of Chimney Height (**Appendix B**). It should be noted in certain cases, dispersion modeling needs to be carried out to determine the safe stack height.

MODULE 5

APPROVAL REQUIREMENTS BY DOE

MODULE 5

APPROVAL REQUIREMENTS BY DOE

LEARNING OUTCOMES:

- ✓ Describe the approval requirements by DOE for setting up of incinerator plant
- ✓ Explain the licensing requirements for incinerator
- ✓ Identify the required inspection prior to approval

5.1 Approval Process

The approval process for installation and operation of incinerator involves the following:

5.1.1 Environmental Impact Assessment (EIA)

Incinerator plant is one of the prescribed activities that require Detailed Environmental Impact Assessment (DEIA) study.

a) Site selection

Based on the Guidelines for The Siting and Zoning of Industries by the Department of Environment (DOE), the incinerator plant is categorized as heavy industry. Thus, incinerator plant is preferably to be located in heavy industrial areas.

For heavy industries, a minimum buffer zone is set at 500 meters from residential areas, livestock farms, agricultural farms, recreation areas and tourist designated areas.

b) Feasibility study

Feasibility study should take into consideration the following factor:

i) Technical

Technical factor includes process and technology selection. Process selection comprises of gasification (starved air combustion), pyrolysis or combustion. Available incinerator technology includes fluidized bed, rotary kiln, stoker, fixed hearth. The following factors should be considered when selecting the suitable incinerator technology:

- Commercial availability: Is the technology available for capacity required? Design limit for capacity required i.e. maximum diameter for fluidized bed for commercial operations < 3 m
- Track record: similar plants elsewhere
- Plant footprint: area required to set up system and auxiliary facilities

ii) Economical
- Capital cost
- Operating and maintenance cost
- Availability of spare parts and local support services
- Haulage cost: Locations of waste sources
- Residual wastes disposal cost

iii) Environmental
- Emissions to air: Air pollution control devices used and performance; can the system comply with new emissions limits by DOE (draft Clean Air Regulations)
- Emissions to water: Does the process generate wastewater? Can the wastewater be recycled back to the combustor and discharged as water vapour?
- Noise generation: Does the system generates excessive noise
- Residual wastes: Generation of ash and impacts (during storage, transport and disposal)
- Health: Impact of emission from incinerators, in particular air pollution to the public health

iv) Socio-economic
- Siting and buffer zone criteria
- Impact on land use and depreciation in adjacent property values
- Social acceptance
- Impact on land traffic

c) Scoping of Key Studies

The scoping of key studies for development of incinerator plant is as follow:

i) Land Use
- Sufficiency of buffer zone
- Compatibility with surrounding industries

ii) Air Quality and Odour
  - Odour from wastes storage and intermediate storage
  - Point source discharge: Chimney emissions, design of APC system and performance, design discharge limits
  - Non-point source discharge: Fugitive emissions i.e. ash handling

iii) Noise and Vibration
  - Generation of noise from plant machineries

iv) Wastewater Discharge
  - Wastewater generation due to washing / rinsing activities
  - Design of wastewater treatment plant and performance
  - Design discharge limits

v) Quantitative Risk Assessment
  - Storage of wastes
  - Storage of flammable materials
  - Risk contours

vi) Biological Environment
  - Adjacency of aquatic ecosystems
  - Impact on wastewater discharge on aquatic ecosystems and fishery activities

vii) Land Traffic and Transportation
  - Transportation routes for waste collection lorries
  - Level of service of road network traversed
  - Impacts on existing congestion and required upgrading works

viii) Socio-economic
  - Public acceptance on development of plant
  - Degradation in property and aesthetic value

ix) Public health
  - Potential increase in related health impact i.e. respiratory / water-borne diseases
  - Risk groups

d) Terms of Reference (TOR)

In preparing a project-related and site-specific TOR for the Detailed EIA study, the project proponent and EIA Consultant shall be able to identify key issues related to the project being proposed. The contents of TOR are outlined as follow:

i) Project proponent
ii) List of Consultants/Study Teams
iii) Statement of Need
iv) Project Description/Concept
v) Project Options
vi) Description of Existing Environment
vii) Baseline information on the proposed location
viii) Project Location and Existing Landuse
ix) Potential Significant Impacts
x) Mitigation and Abatement Measures
xi) Residual Impacts
xii) Environmental Management Plan (EMP)

The key assessment criteria for DEIA study are shown in**Table 5-1**. Meanwhile, the key approval criteria for DEIA study have prioritized assessment as shown in **Table 5-2**.

Table 5-1: Key assessment criteria for DEIA study

Criteria	**Assessment**
Land Use	Buffer zone met?
Air Quality and Odour	Does odour from wastes impact adjacent sensitive receptors? Pollutant dispersions: Does concentrations of air pollutants reaching sensitive receptors below ambient limits during normal operation? What is the maximum GLC of air pollutants and locations of occurrence? In worst case scenario (release of untreated gases), does the concentrations of air pollutants reaching sensitive receptors still below ambient limits? What is the probability for occurrence of worst case scenario and preventive action in place (i.e. automatic cut off system)?
Wastewater Discharge	Does the treated effluent discharge met relevant DOE limits? Does the release of untreated effluent results in irreversible damage to aquatic environment and fishery activities? What is the probability for occurrence of worst case scenario and preventive action in place (i.e. automatic cut off system)?
Quantitative Risk Assessment	Does the individual and society risk contours within DOE limits? If not, what are the extra mitigating measures put in place?
Land Traffic and Transportation	Can the transportation route handle the increase in traffic from the Project
Public health	Does the communities within 5-km radius of the site already exposed to respiratory and/or water-borne diseases from other industries? Can the communities absorb further impacts from current Project?

Table 5-2: Key approval criteria for DEIA study

Criteria	**Assessment**
Statement of Need	Does the need for the incinerator justified? Has other disposal options been considered and exhausted?
Capacity	License capacity requested Ability to cater for future growth Diversion of wastes in the event of breakdown
Air Quality and Odour	Can the proposed APC system meet the emissions limits as per draft CAR? Track record of APC in similar plants elsewhere i.e. emissions data
Wastewater Discharge	Can the proposed WWTP meets the discharge limits as per Environmental Quality (Effluents) Regulations 2009 i.e. Standard A or B Track record of APC in similar plants elsewhere i.e. effluent data
Quantitative Risk Assessment	Is the individual risk contained within the plant boundaries? Is the societal risk contained within industrial area?
Land Traffic and Transportation	Coordination of required upgrading works required for transportation route to cater for traffic growth due to waste trucks
Public health	Community health programme and commitment of Project Proponent to conduct periodical health survey on surrounding community to ensure minimal impacts on their health due to operation of the incinerator

5.1.2 Written approval

The written approval is required for the following key components:-

a. Premises
b. Incinerator system
c. Boiler
d. Air Pollution Control (APC) System c/w Chimney
e. Standby generator set
f. Wastewater Treatment Plant (WWTP)

Based on new Environmental Quality (Industrial Effluents) Regulations 2009, the requirement for WA is abolished for WWTP. Instead, an application to set up a WWTP is to be made by Project Proponent to the Director Generator of Environmental Quality, whereby the application shall be attached by design drawings endorsed by Professional Engineers in Civil/Structural, Chemical/Environmental and Electrical Engineers.

The related written approval forms for each component are attached in **Appendix C**.

For processing of written approval applications, the following items need to be paid attention:

- Types of form to be used
- Key data/information to be provided by applicant
- Critical assessment criteria for approval

5.1.3 Licensing

In order to obtain license for installation and operation of incinerator, consideration should be given to the relevant agencies involved and incinerator design capacity.

a) Relevant agencies

Ministry of Health has granted concession to the following companies to handle clinical waste (storage, collection, transportation, **treatment (incineration)** and disposal)

- Faber Medi-Serve Sdn Bhd (Northern region)
- Radicare (M) Sdn Bhd (Central region)

  - Pantai Medi-Vest (Southern region)
- DOE has granted concession to Kualiti Alam (KA) for Scheduled Waste (SW) incinerators

b) Design capacity

The capaciy required need to be justified by waste projection study.

5.2 Considerations of Incinerator Licensing

5.2.1 General design requirements

In order to obtain license, incinerator plant should provide a detailed engineering data which includes:

- Manufacturer of incinerator
- Type of waste to be burnt
- Type of fuel
- Fuel consumption rate
- Incinerator capacity
- Size of primary and secondary chamber
- Retention time in secondary chamber
- Combustion temperature in primary and secondary chamber
- Minimum limit of chimney height

5.2.2 Waste analysis suitability and acceptance criteria

During license application, plant operator should specify the type of waste to be burnt in his plant. The incinerator plant can only burn the waste that is specified in license condition. For example, clinical waste incinerator plant can only burn clinical waste as defined by Ministry of Health.

5.2.3 Destruction and Removal Efficiency (DRE)

DRE is used to measure incinerator performance. A 99.99 percent DRE means that one molecule of an organic compound is released to the air for every 10,000 molecules entering the incinerator. A 99.999 percent DRE means that one molecule of an organic compound is released to the air for every 1,000,000 molecules entering the incinerator.

Since it would be impossible to monitor the DRE results for every organic constituent contained in a waste, certain principal organic hazardous constituents (POHCs) are selected for monitoring and are designated in the permit. POHCs are selected based on high concentration in the waste feed and difficulty in burning compared to other organic compounds. If the incinerator achieves the required DRE for the selected POHCs, then it is presumed that the incinerator should achieve the same or better DRE for organic compounds that are easier to incinerate.

Such DRE for each POHC are calculated using the following equation:

$DRE = (W_{in}) - W_{out}) / W_{in}) \times 100\%$

where,

W_{in} = mass feedrate of one POHC in a waste feedstream

W_{out} = mass emission rate of the same POHC present in exhaust emissions prior to release to the atmosphere

5.2.4 Automatic Waste Feed Cut-Off & Process

Waste feed cut-off is a system to cut off waste feed automatically when key operating conditions deviate from the limits established in the license. These include carbon monoxide, combustion temperature and normally excess oxygen, combustion gas velocity, critical APCS control parameters and others determined by DOE to ensure that the required performance standards are met.

5.2.5 Flue Gas Temperature

The flue gas temperature exiting from chimney should be maintained above acid dew point. This is to avoid condensation of flue gas which will emit white smoke or plume. The discharge temperature is normally around 120°C.

5.2.6 Puffing and Emergency Venting

Emergency venting is normally used during power trip. The air emission will exceed the specified limits, however the effect is minimal since complete combustion of waste can be achieved within 30 minutes.

5.2.7 Slagging

Slagging occurs when operating temperature is above the melting point of ash, typically above 1200°C. The potential causes of slagging are temperature and low melting point salt such as potasssium and sodium which can reduce the fusion ash temperature.

The melt ash will fuse or solidify at low temperature producing molten slag (**Figure 5-1**). Slagging mainly cause accumulation of fused deposits in boiler tubes and ductwork. To prevent slagging occurrence, the waste heat boiler inlet temperature should be reduced below 800°C to avoid the ash from sticking to refractory.

The corrective action for slagging is cleaning up of boiler tubes and ducting.

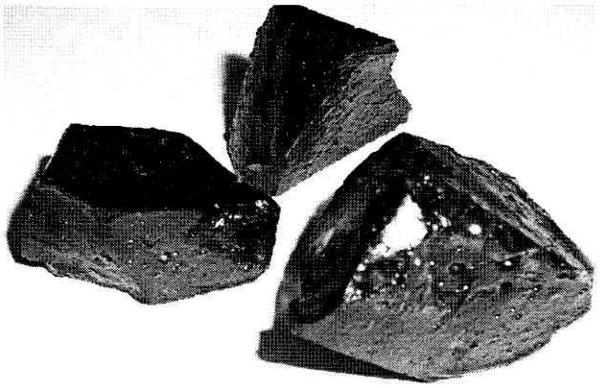


Figure 5-1: Molten slag from solid waste incinerator

5.2.8 Required Plans on Application

5.2.8.1 Waste analysis plan

The procedure for waste sampling programme is attached in **Appendix D**. After waste sampling, waste analysis based on ASTM methods is conducted to determine the following parameter:

- Moisture content
- Proximate analysis
- Ultimate analysis
- CV content

Sample of waste analysis results is attached in **Appendix E**.

5.2.8.2 Prepared prevention plan

The scenarios that require prevention plan are as follow:

i. Fire / explosions
ii. Traffic accidents involving waste collection trucks
iii. Spillage / leakage of wastes (onsite / offsite)

The plan should include the following:

i. Delegation of task and responsibility of key personnel
ii. Standard Operating Procedures (SOP)

5.2.8.3 Contingency Plan

Types of contingency:

i. Fire / explosions
ii. Traffic accidents involving waste collection trucks
iii. Spillage / leakage of wastes (onsite / offsite)
iv. Power interruptions

Incinerator plant must have insurance throughout license period that covers spillage/ accidents/fire and clean up cost for scheduled waste. A copy of insurance should be submitted to state DOE within 2 months after license is given. In addition, an Emergency Response Plan (ERP) should be prepared and a copy must be submitted within 1 month after license is given.

Any spillage/ accidents/fire should be immediately controlled and informed to Ketua Pengarah Kualiti Alam Sekeliling (KPKAS) and state DOE Director within 24 hour.

5.2.8.4 Personnel Protection Plan

Incineration of hazardous waste (i.e. clinical waste) may pose health risks to incinerator personnel. The following are examples of protection plan:

a. Jurisdiction bodies: Deapartment of Safety and Health (DOSH) and MOH
b. MOH: Immunisation programme
c. DOSH: Exposure to high noise levels, chemicals etc

5.2.8.5 Personnel Training Plan

Examples of personnel training are as follow:

a. Health, Safety & Environment (HSE) Policy Awareness
b. Environmental Protection i.e. Environmental Management System (ISO 14001)
c. Health and Safety Protection i.e. OHSAS 18001
d. Frequency of training and re-training

The typical training programmes include:

i. Evacuation plan during fire / explosion outbreaks
ii. Chemical handling
iii. Proper use of personnel protective equipment (PPE)
iv. Clean-up of spillages / leakages
v. Emergency bypass situations → critical for shift managers / operators

5.2.8.6 Equipment Inspection, Monitoring & Maintenance Plan

The following records need to be prepared in inspection plan:

i. Records for DOE inspections (log books)
ii. Records for plant operational functions

Monitoring programme is required to ensure that the incinerator plant complies with DEIA / EMP / KB approval conditions. Example of monitoring programme is shown in **Table 5-3**.

For maintenance plan, a copy of “Standard Operating Procedure (SOP)” for the maintenance of incinerator plant shall be prepared and submitted to state DOE. The maintenance and management shall be carried out/managed by qualified operator(s) whom are responsible to ensure all regulations and stipulated standards are complied with.

Table 5-3: Example of monitoring programme for incinerator plant

No	Monitoring components	Number of Stations	Frequencies of sampling
A	**Periodical Monitoring By Third Party**		
1	Chimney emissions	1	Continuous* and Quarterly
2	Effluent from wastewater treatment plant	1	Monthly
3	Boundary noise level	4	Annually
4	Ambient air quality	2	Quarterly
B	**Regular Monitoring By In-House Staff**		
1	Performance of bag filter system	1	Daily
2	Performance of wastewater treatment plant	1	Daily
3	Solid waste disposal	(plant-wide)	Weekly
4	Scheduled waste disposal	(plant-wide)	Monthly
5	Storage of chemicals and scheduled wastes	(plant-wide)	Daily
C	**Periodical Auditing (In-House or Third Party)**	(plant-wide)	Annually

*With the installation of Continuous Emission Monitoring System (CEMS)

5.2.8.7 Trial Burn Plan

The trial burn is conducted to test the incineration process and to demonstrate compliance with regulatory requirement when operating under specific test condition. The waste sources for trial burn should be representative of actual incoming wastes. Trial burn is conducted under relevant regulatory bodies supervision.

Trial burn involves the sampling and analysis of waste feeds to determine the input rate of each constituent for which performance will be determined (i.e. POHCs, metals, chlorine, etc), while simultaneously sampling and analysing the stack exhaust gases to determine the constituent emission rates. From the input rates and emission rates, the control efficiency can be calculated, compliance with emission standards can be determined and where appropriate limitations on feed rates can be established.

During trial burn, stack emission testing is carried out for gases emission, particulate matter, hydrogen chloride, heavy metals, total organic carbon (TOC), dioxin/furan and DRE.

5.2.8.8 Performance Testing Plan

The purpose of performance testing is to allow verification of compliance with standard emission limits. The sampling programmes for performance testing include:

i. Flue gas sampling before and after APC
ii. Bottom ash analysis
iii. Fly ash analysis

The performance parameters to be measured are

i. DRE
ii. Flue gas concentrations before and after APC (removal efficiency for each pollutant)
iii. Loss on ignition (carbon content) in fly and bottom ashes

5.2.8.9 Abandonment Plan (Post-Closure Plan)

Abandonment means termination of plant operation due to the following scenarios:

- End of plant lifespan
- Shifting of plant to another site
- End of business entity i.e. bankruptcy etc

Plant operator has to give out closure plan that details out the steps to be taken for closure (i.e. EMP, outline of potential critical impacts to environment i.e. contamination of soil / groundwater / accumulation of SW) for approval from Ketua Pengarah Kualiti Alam Sekeliling (KPKAS).

The closure plan should be submitted at least 120 days before commencement of closure works. Decommissioning activities should be carried out in accordance with the approved closure plan within 180 days after approval by KPKAS.

5.3 Quality assurance or control plan

a. Performance guarantee from suppliers for major equipment
    i. Incinerator
    ii. Air Pollution Control Equipment
    iii. Wastewater Treatment Plant

b. Quality Control Committee
    i. Preferable: Experienced experts in relevant field to review technical information
    ii. Engagement of representatives from regulatory bodies
    iii. Operating team for proposed incinerator plant

5.4 Inspection Prior to Approval

a. Trial burn
    i. Regulatory limits: EIA / KB approval limits by DOE
    ii. Operating limits: Allowable operating range
    iii. During trial burns: Typical sampling worksheets

b. Troubleshooting
    i. Potential issues
    ii. Proposed onsite action plans
    iii. Criteria for abandonment of trial burn (worst-case)
    iv. Wastes not representative
    v. Equipment not according to specifications
    vi. Equipment malfunctions

c. Continuous emission monitors (CEMS)
    i. Types of CEMS used
    ii. Parameters monitored and detection limits
    iii. Calibration and reliability of data
    iv. Record keeping
    v. Online system to DOE

d. Environmental management system (EMS)
    i. Committee: Personnel-in-charge, tasks and responsibility
    ii. Environmental considerations of inputs / outputs

e. Inspection checklist
    i. Setting up of checklist and key assessment criteria
    ii. Review and approval for implementation

MODULE 6

PERFORMANCE MONITORING

MODULE 6

PERFORMANCE AND EMISSION MONITORING

LEARNING OUTCOME:

- ✓ Describe the performance and emission monitoring carried out at incinerator plant
- ✓ Describe the performance requirement for incinerator plant
- ✓ Explain incinerator control system
- ✓ Explain the type of sampling and monitoring equipment

6.1 Performance monitoring

6.1.1 Operating standard and parameters

6.1.1.1 Allowable capacity of wastes to be burnt

The amount of waste that can be burnt in incinerator plant should not exceed the amount that is approved by DOE.

6.1.1.2 Destruction and Removal Efficiency (DRE)

DRE is actually a measure of how much pollutants coming out from chimney (i.e. the emission). It is used by US EPA to measure the performance of incinerator plant. The sampling location for DRE is normally at the stack level before discharge into atmosphere.

However, in Malaysia, DRE may not be relevant since we have the standard emission limits that must be complied by incinerator plant.

6.1.1.3 Carbon dioxide efficiency and carbon monoxide monitor

CO needs to be monitored because it is indicator of combustion completeness. The combustion efficiency can be calculated using the following equation:

$$\text{Combustion efficiency} = \frac{CO_2}{CO_2 + CO} x100$$ **Equation 6-1**

CO and CO_2 should be measured immediately after the secondary combustion chamber. If a waste heat boiler is installed, the CO and CO_2 monitors may be placed after the boiler to minimize sampling and gas conditioning problems.

6.1.1.4 Temperature range to be maintained in incinerator

The minimum combustion temperature in incinerator is critical to achieve high-efficiency combustion and destruction of organic materials. **Table 6-1** shows the minimum temperature required for combustion in secondary chamber meanwhile for primary chamber, there is no specification on minimum temperature. Incinerators should be capable of sustaining, on a continuous basis, an incineration temperature about 100°C greater than the minimum temperature.

Table 6-1: Minimum temperature in secondary chamber required for combustion of waste in incinerator

Type of waste	Minimum temperature, °C
Chemical waste	**850**
Clinical waste	**1000**
Municipal solid waste	**850**
Animal carcasses	**850**
Sewage sludge	**850**
Drum waste	**850**

Auxiliary burners should be incorporated into the design to ensure that the minimum operation temperature is maintained. The burners should be operated at the following phases:

a) at start-up before the commencement of the incineration cycle;
b) during shutdown until all combustion of waste has ceased; and
c) when necessary during other phases of operation

6.1.1.5 Flue gas temperatures to be maintained along duct

The temperature of flue gas exiting secondary chamber is normally high, around 900°C. After passing through waste heat boiler, the temperature will be reduced to the temperature allowable for entering dust collection device. However, the temperature must be maintained above dew point temperature to avoid condensation of flue gas.

6.1.1.6 Pressure

Combustion chambers, casings, ducts and ancillary equipment should be made as gas-tight as practicable. They should be maintained under slight reduced pressure and designed to prevent both the release of gases and disturbance of combustion conditions during waste charging. Control of the induced draft fan, primary air and the feed rate are the primary considerations.

6.1.1.7 Oxygen level

Air is an important factor in incineration process. The common terms of air requirement encountered when dealing with incineration process are defined as follow:

a) Stoichiometric air

In the chemical reaction between organic materials and oxygen, stoichiometric oxygen demand or theoretical is the amount of oxygen required under ideal or perfect conditions to burn all of the organic materials with no oxygen left over.

b) Excess air

High-efficiency destruction (oxidation) of any combustible material requires that more oxygen be present than what is required by the chemistry of the process. Air feeding greater than those required at stoichiometric level is called excess air. The percent of excess air required varies with type of fuel as shown in **Table 6-2**.

Table 6-2: Excess Air at Furnace Outlet

Fuels		Percent Excess Air
Gaseous	Natural Gas	5-10
	Refinery Gas	8-15
	Blast Furnace Gas	15-25
	Coke Oven Gas	5-10
Liquid	Oil	3-15
Solid	Coal (Pulverized)	15-30
	Coke	20-40
	Wood	25-50
	Bagasse	25-45
	MSW (Excess Air)	40-50
	MSW (Starved Air)	130-150

c) Starved air

Air feeding less than those required at stoichiometric levels is called deficient air or starved air.

Incinerators and their air distribution systems is normally designed and operated to provide an oxygen rich atmosphere of more than 6% O_2 in the combustion zone. Oxygen level can be determined using oxygen sensor. Types of oxygen sensor are as follow:

- Zirconia sensor (**Figure 6-1**)

  The ceramic material zirconia (ZrO_2) when heated above about 600°C becomes an oxygen ion conductor. The most common form of this type oxygen analyser comprises a probe mounted zirconia element inserted into the flue duct.

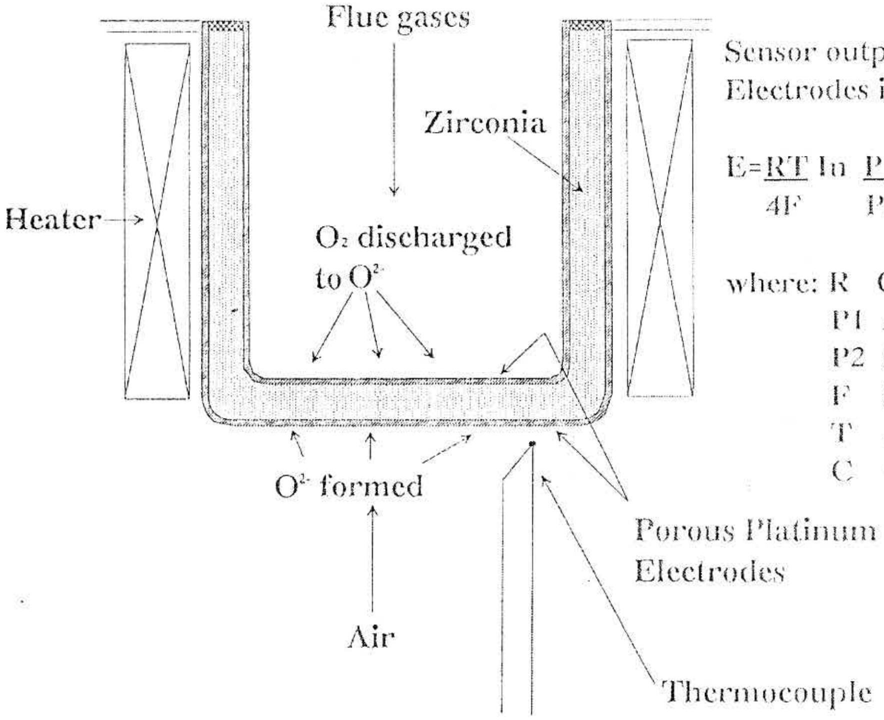
- Paramagnetism (**Figure 6-2**)

  Oxygen is unusual in having unpaired electrons and this gives it its property of paramagnetic susceptibility. Paramagnetic substances are attracted to the strongest part of a magnetic field.

  Paramagnetic oxygen analysers are reliable devices providing they are supplied with clean, dry gas. They are commonly used as stand alone portable analysers, rack mounted analysersand are sufficiently compact to be incorporated in a single unit with infraed analysers for ather gases.

- Low temperature electrochemical cell (**Figure 6-3**)

  Electrochemical cell has a cathode, anode and an aqueous electrolyte. When electromagnetic field is applied to it, oxygen evolves at the anode and hydrogen at the cathode. Its operation in the reverse mode is the basis of galvanic oxygen sensors.



Sensor output across Electrodes is given by:

$$E = \frac{RT}{4F} \ln \frac{P1}{P2} + C$$

where:
R Gas Constant
P1 Air Oxygen Level
P2 Flue Gas Oxygen Level
F Faradays Constant
T Absolute Temperature
C Cell Constant

Figure 6-1: Zirconia sensor

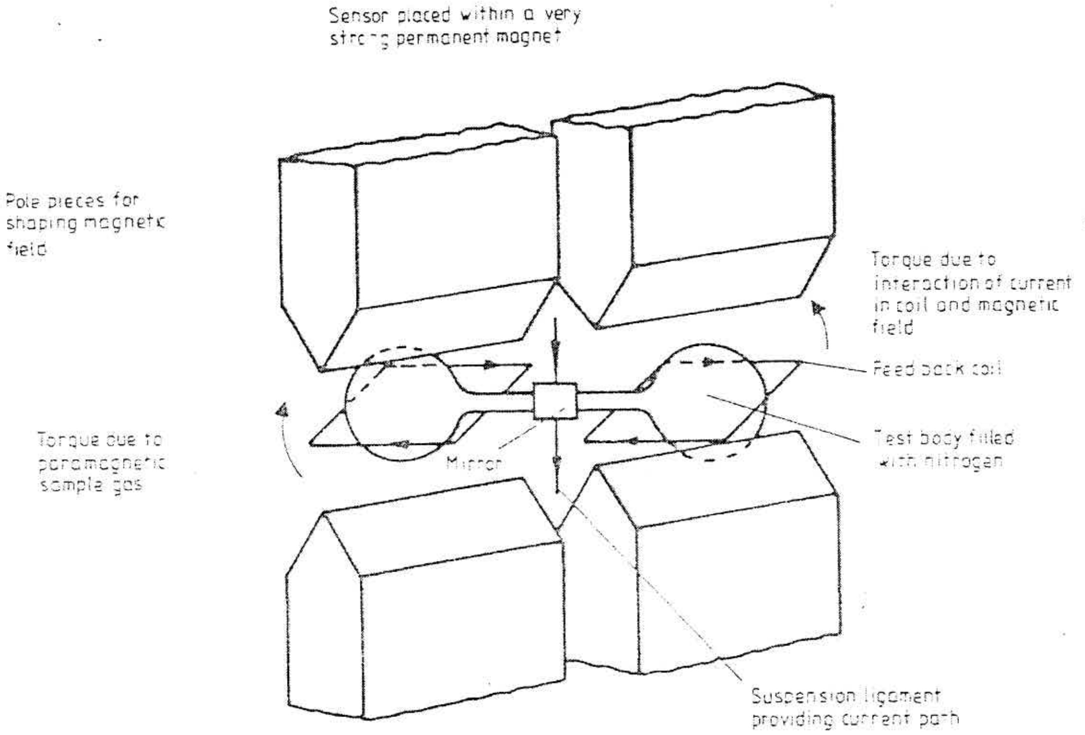


Figure 6-2: Paramagnetism

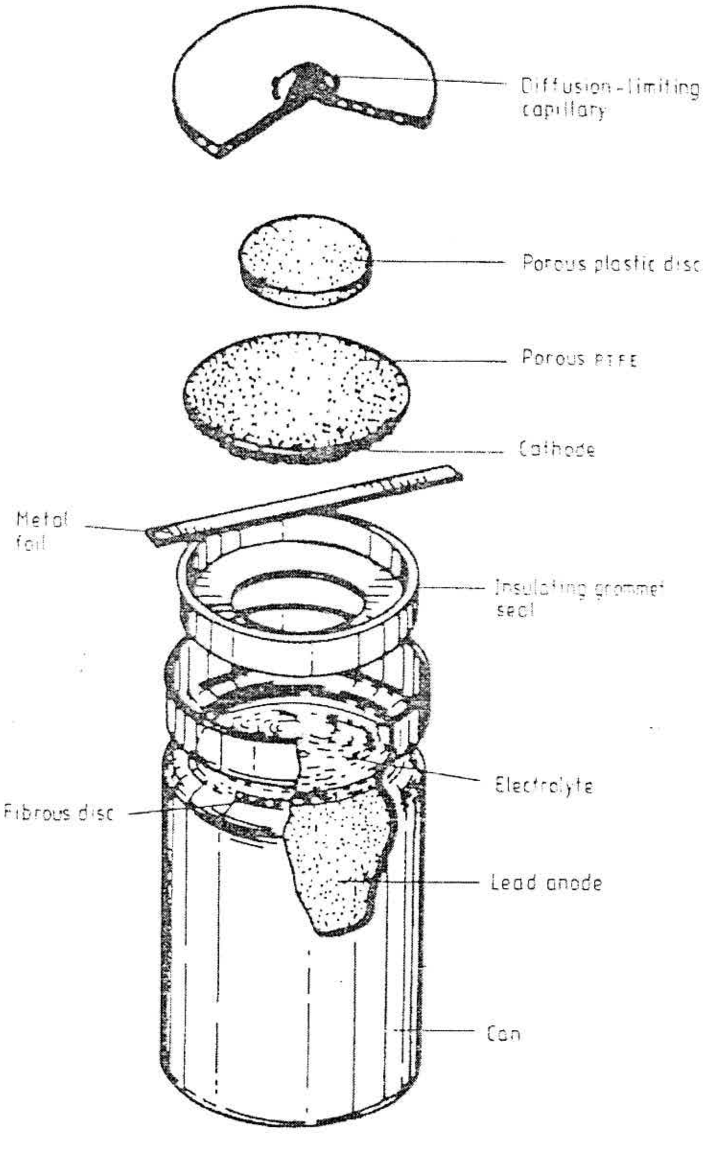


Figure 6-3: Low temperature electrochemical cell

6.1.2 Incinerator control system

Incinerator is normally equipped with automatic control and alarm systems (i.e. visual and audible) in conjunction with the monitors for temperature, oxygen and carbon monoxide. Such control system is illustrated in **Figure 6-4**.

CO detector is linked to waste feeding system. High CO indicates incomplete combustion. When high CO is detected, waste feeding is automatically stopped until acceptable CO level is achieved.

O_2 sensor is linked to primary and secondary air fan. Whenever low O_2 is detected (i.e. less than 6%), the air fans will automatically inject more air to achieve the required level.

Thermocouple is connected to burner system so that temperature in furnace can be controlled. Burner will be activated when furnace temperature is below requirement and vice versa.

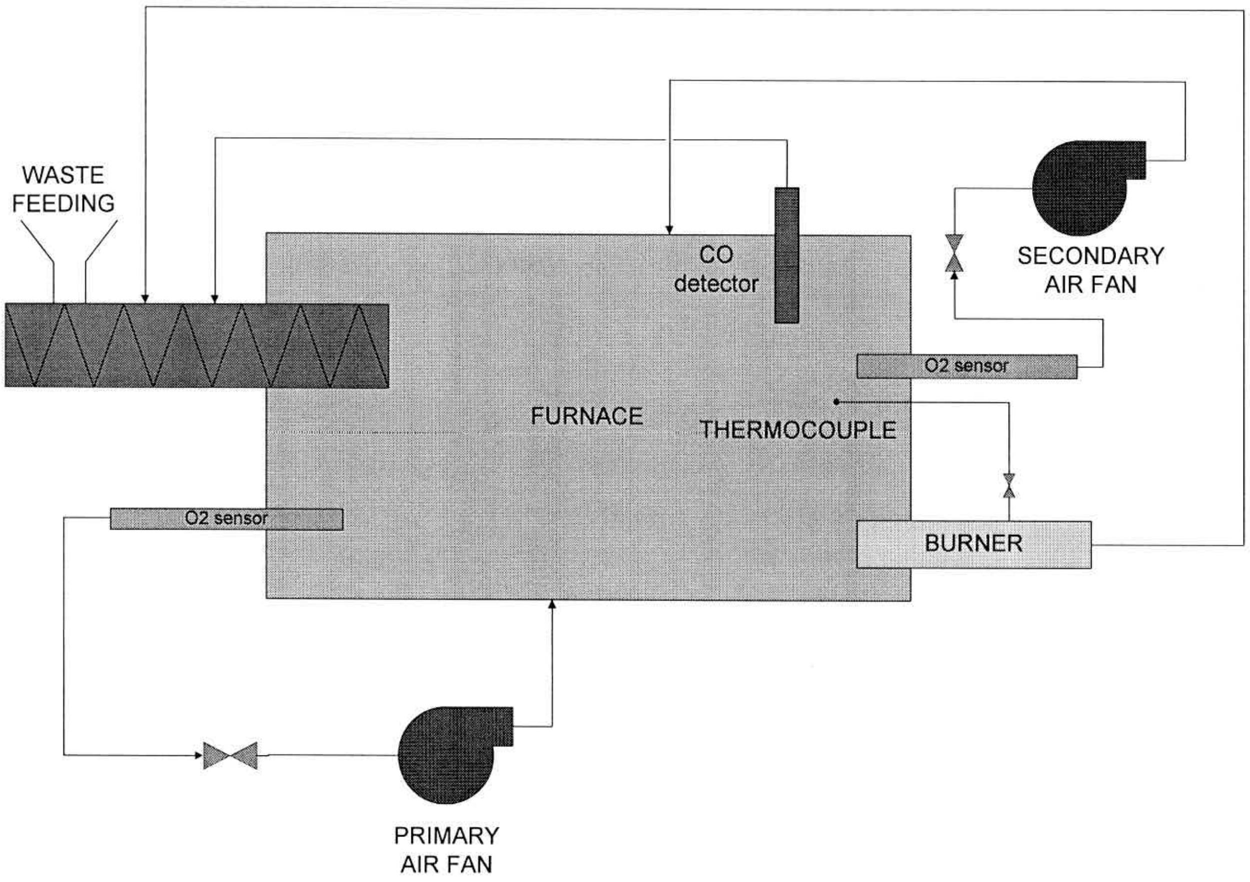


Figure 6-4: Control system in incinerator plant

6.2 Emission monitoring

6.2.1 Monitoring of pollutants

Monitoring must be conducted for pollutants specified in the new CAR for incinerator plant (**Figure 1-1**). The list of US EPA Methods for emission measurement is attached in **Appendix F**. Continuous monitoring has to be conducted for the following pollutant emissions:

- Dust
- HCl
- SO_2
- CO
- CxHy
- NOx
- HF

Pollutants such as heavy metals and PCDD/F are monitored on a regular basis (minimum of 2 to 4 times per year).

6.2.2 Limit concentrations for regulated air pollutants at point of discharge (chimney)

The concentrations limits for air pollutants discharged from chimney should comply with the new Clean Air Regulation (Fourteenth Schedule) for incinerator process as shown in Module 1. Concentrations of pollutant are required to be corrected to 11 % oxygen to avoid incinerator plant attempting to comply with the stipulated limits by means of air dilution (i.e. more air is supplied to reduce the concentration of pollutants).

6.2.3 Sampling of pollutants

There are two sampling methods such as follow:

- Manual
- Continuous (Instrumental analysis)

6.2.3.1 Manual sampling method

Manual method involves the usage of sampling train. Typical sampling train for universal source sampling is specified under US EPA Method 5 as shown in **Figure 6-5.**

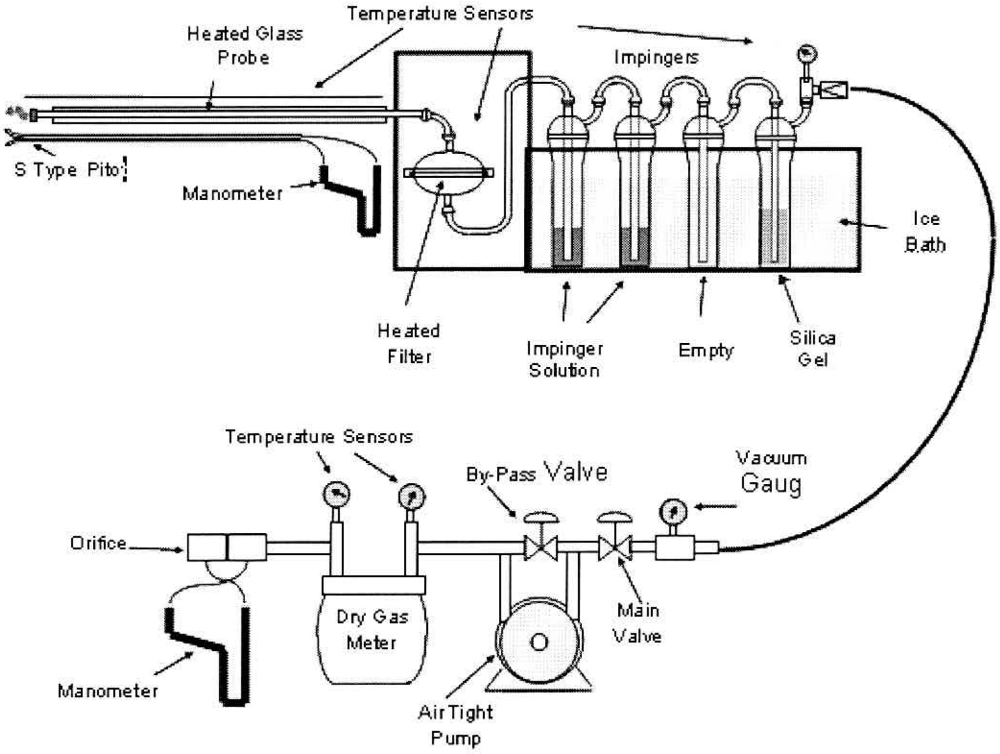


Figure 6-5: Universal sampling train (US EPA Method 5)

The following pollutants can be sampled using manual methods.

a) Sampling of total particulate

The in-stack particulate concentration is measured using MS 1596: 2003; “Determination of concentration and mass flow of particulate matter in flue gas for stationary sources emissions”, in accordance with US EPA Method 5: “Determination of particulate emissions from stationary sources” whereby a measured volume of stack gas was withdrawn isokinetically through a nozzle which has a sharp and tapered leading edge. Particulate matter is collected on a pre-weighed glass fibre filter located in an oven set at temperature of 110°C above the dew point of water to avoid water vapour from condensing. The concentration of particulate matter in the stack gas is determined by the difference in weight of the filter before and after sampling.

b) Acid gases

The determination of acid gases (HCl, HF, HBr) in the stack gas is carried out using the US EPA Method 5 sampling train whereby a measured volume of stack gas is withdrawn isokinetically through two impingers each containing 100 ml chilled 0.1N H_2SO_4 and 0.1N NaOH.

Solutions of H_2SO_4 and NaOH are analysed for chloride, fluoride and bromide using DR 4000 spectrometer following HACH method 8113. The total chloride, fluoride and bromide response are expressed as HCl, HF and HBr respectively. Procedures equivalent to US EPA 26A: "Determination of hydrogen halides and halogen emissions from stationary sources – isokinetic method.

c) Heavy metals

The determination of heavy metals such as Arsenic (As), Cadmium (Cd), Copper (Cu), Mercury (Hg), Lead (Pb), Chromium (Cr), Zinc (Zn), Nickel (Ni), Antimony (Sb) in the stack gas is carried out using the US EPA Method 5 sampling train whereby a measured volume of stack gas is withdrawn isokinetically through a series of two impingers each containing 100 ml of chilled potassium permanganate-nitric acid solution and deionized water, respectively. Both the filter and absorbing solutions are analyzed for heavy metals using the following technique (US EPA SW-846):

- Arsenic and antimony are determined by hydride generation atomic absorption spectroscopy
- Cadmium, copper, lead, chromium, nickel and zinc are determined by flame atomic absorption spectroscopy
- Mercury is determined by cold vapor atomic absorption spectroscopy

d) Dioxins/Furans

The regulatory method for sampling and analyzing offgas dioxins/furans is US EPA Method 23. For Method 23, the offgas sample is passed through a filter to retain any particulate-bound dioxins/furans, and a resin cartridge to adsorb any vapor phase dioxins/furans (**Figure 6-6**).

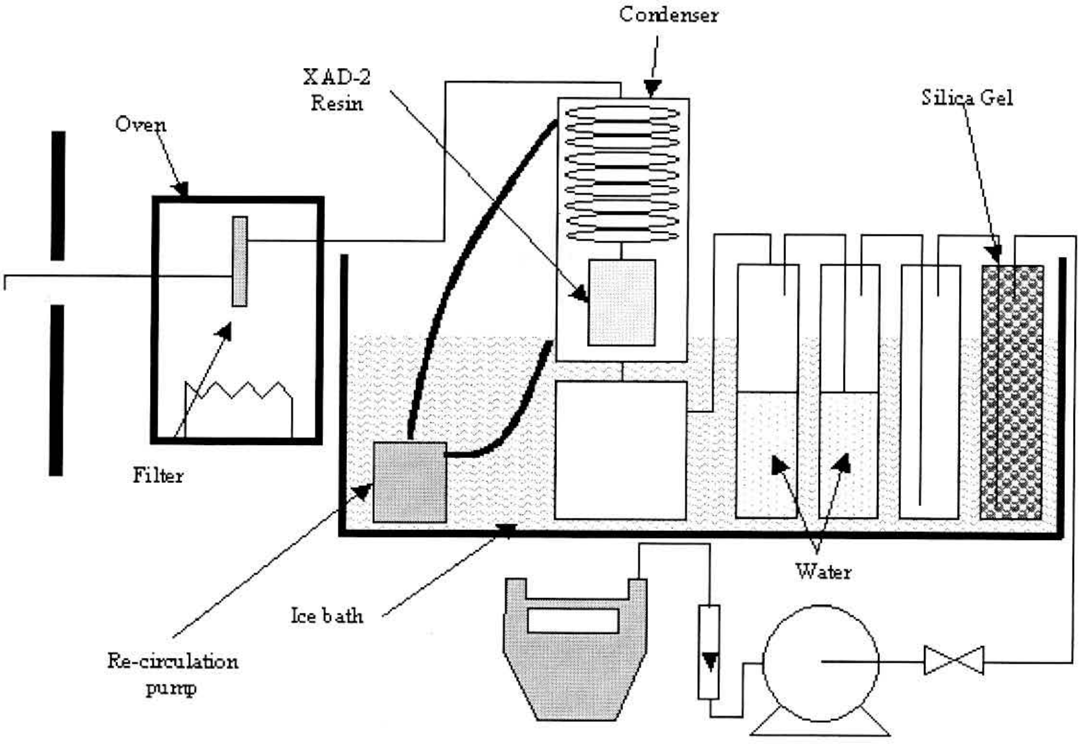


Figure 6-6: Sampling train (US EPA Method 23)

6.2.3.2 Continous sampling method (Instrumental analysis)

Gas analyzer is the example of continuous sampling method. It measures component of flue gas such as O_2, CO_2, CO, NO, NO_2 and SO_2. There are two types of gas analyzer such as follow:

- Extractive
- In situ

a) Extractive analyzers

A sample from the flue or chimney is extracted and conditioned before passing it through either infrared, ultraviolet or chemiluminescence analyzers. There are two categories of extractive analyzer:

- Samples are extracted and then conditioned, including chilling to remove condensate, before the analysis takes place.
- Extracted sample is kept above the dewpoint of the gas, and passes through instruments which are capable of measuring hot gas.

This method has disadvantages such as follow:

- Non-representative because the sample is modified to remove water and other components within the sample.
- The system response rate is not very fast.
- High maintenance cost for measuring instruments and sample preparation system.

One example of extractive methods is the portable gas analyzer (TELEGAN, Tempest 100) (**Figure 6-7**). The equipment operates by drawing in a small sample of stack gas to be detected by a number of gas sensors. The analysis of the gas is based on group electrochemical cells equipped with a selective diffusion membrane. Readings of the parameters are recorded every one minute over a period of 5 minutes, and then average to obtain average concentrations of each gaseous component. The methods are equivalent to US EPA Method 3A, 6C and 7E: "Determination of O_2 and CO_2 concentrations in emissions from stationary sources (instrumental analyzer procedure)", "Determination of sulfur dioxide emissions from stationary sources (instrumental procedure)", and "Determination of nitrogen dioxide emissions from stationary sources (instrumental procedure)" respectively.

Figure 6-7: Portable gas analyzer (TELEGAN, Tempest 100)

b) In situ analyzers

In situ analyzers include a type in which a sensor is mounted in the flue or which use cross-duct optical methods. They work on the principle of sending a pulsed infrared or ultraviolet light beam across the duct where measurement takes place.

These systems have the advantage that they avoid the need to extract a sample from the stack and analyze an unmodified and truly representative gas sample. In addition, the response rate is rapid, because the lag in transporting the sample has been eliminated.

However, installation costs for in situ analyzers are comparatively high especially when the optical path is situated high up on a stack. Another disadvantage of in situ analyzers is that they are prone to optical misalignment due to expansion and warping of the duct wall.

An example of in situ analyzer is the enveloped, folded beam analyzer which is developed by Procal Analytics Ltd UK (**Figure 6-8**) which is also referred as continuous emission monitoring system (CEMS). CEMS is generally a packaged system of gas analyzers, gas sampling system, temperature, flow and opacity monitors that are integrated with a data aquisition system to demonstrate environmental regulatory compliance of various industrial sources of air pollutants.

CEMS is used in incinerator plant to monitor emissions such as sulfur dioxide, nitrogen oxides, carbon monoxide, carbon dioxide, hydrogen chloride, particulate matter, mercury, volatile organic compounds, and oxygen to provide information for combustion control. CEMS can also measure air flow, flue gas opacity and moisture.

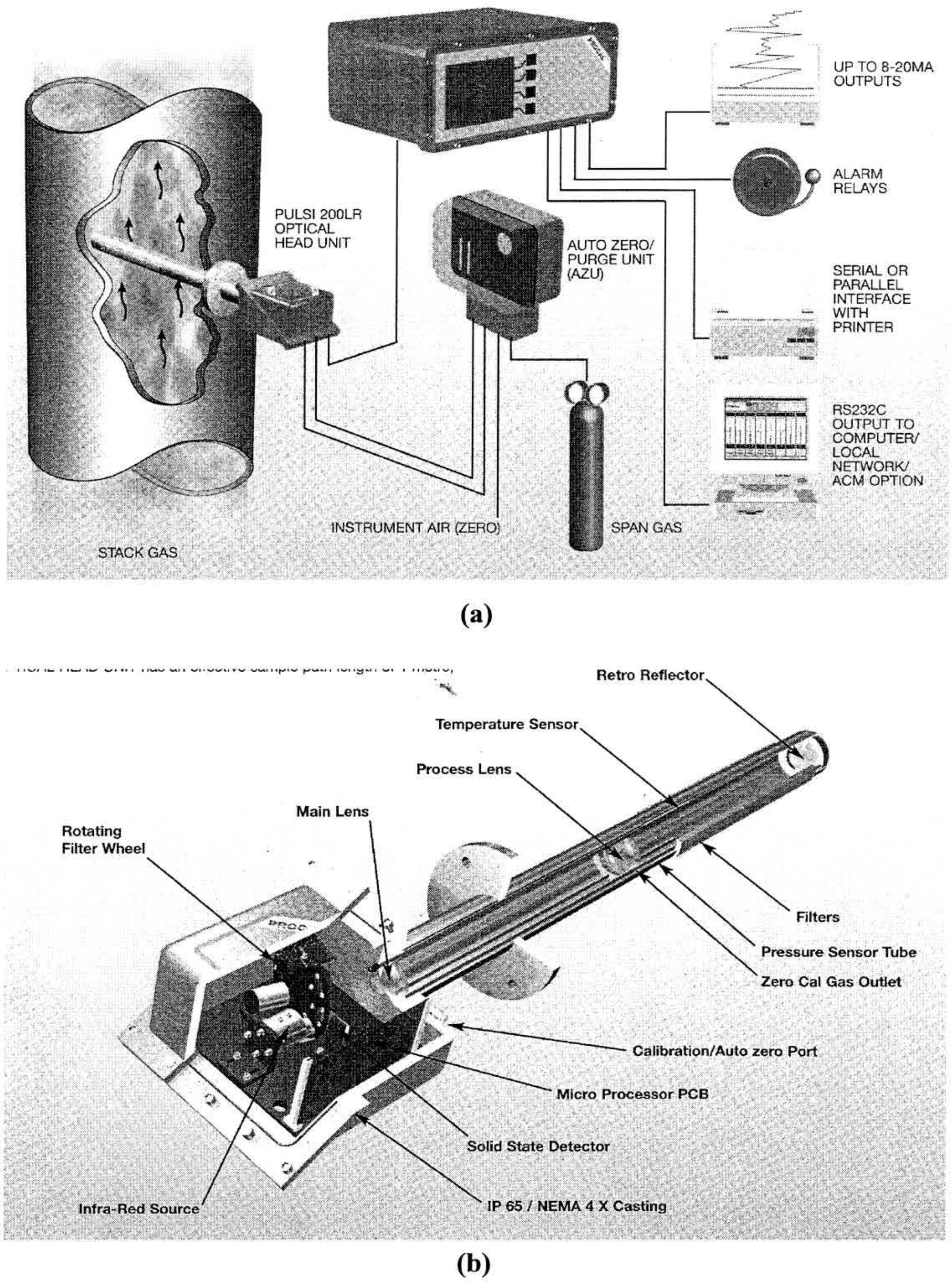


Figure 6-8: (a) In situ gas analyzer system; (b) Cross section of head unit

6.2.3.3 Reliability of data and cross-checking

The reliability of monitoring data should be assessed. One way to do this is by cross-checking the data from CEMS that is installed at incinerator plant with manual stack sampling.

MODULE 7

INSPECTION

MODULE 7

INSPECTION

LEARNING OUTCOMES:

- ✓ Explain the need for inspection
- ✓ Describe the methods of inspection
- ✓ Able to conduct inspection

7.1 Need of inspection

Inspection of incinerator plant is conducted for the following reason:

a. To determine whether the incinerator plant is operating at optimum level

b. To make sure the incinerator plant comply with DOE's requirements

7.2 Inspection methods

Inspection of incinerator plant is carried out by the following methods:

a. Inspection through observations

b. Inspection of operating parameters

c. Inspection of record keeping

7.2.1 Observations

The inspection involves observation of the following:

a. Waste bed

The waste bed can be observed through spy glass located at primary combustion chamber. If the pile volume of unburned waste is rapidly and/or steadily increasing in quantity, it shows that the amount charged is greater than the amount which can be gasified in the same period of time.

b. Smoke

Smoke emission from incinerator components other than stack might occur because negative pressure is not maintained in the incinerator plant. This is probably due to malfunction of induced draft fan or leaking.

In addition, the smoke color could indicate the reason of smoke emission. Black smoke indicates incomplete combustion of waste due to inadequate oxygen supply.

White smoke or plume indicates condensation due to flue gas temperature lower than dew point temperature. White smoke is not desirable due to the following reason:

- White smoke is visible which people might perceive as pollutant
- Corrosion of refractory material due to condensation of acid gases
- Blinding of filter bag (i.e. accumulation of excesive dust cake on filter media)

c. Noise

The source of noise at incinerator plant might be from mechanical equipment such as induced draft fan, compressor, waste feed ram, etc. Other sources are from incoming trucks, wastewater treatment plant, washing area, etc. Simultaneous operation of noise sources results in higher noise level at incinerator plant.

d. Ash

Ash quality could indicate the combustion efficiency. The term *burnout* is used to describe the level of carbon left in the ash. Low carbon content in the ash indicates good *burnout*. If the total organic carbon (TOC) content in the ash above 10%, disposal at the Kualiti Alam requires incineration of the ash that resulting in higher disposal fee.

If the ash has high carbon content, it may be because the charge rate is too high, poor mixing in primary chamber and not enough time has been provided for complete combustion. Another reason for poor ash quality is insufficient underfire air.

e. Ducting

Ducting that appears to have burn spot and discoloration might indicate damage of insulation or refractory material.

f. Cleanliness

Incinerator plant that handles scheduled waste (i.e. clinical waste) must adhere to scheduled waste handling as required by standard operating procedure (SOP). For instance, clinical waste must always be kept in the provided bin and requires direct tipping from the bin to the combustion chamber. Tipping process is done by waste feed system where manual handling is not allowed.

Breaking and spillage of waste bags might indicate that the waste charging system is not properly operated.

7.2.2 Inspection of operating parameters

Operating parameters that can be inspected at incinerator plant are as follow:

a. Temperature

The combustion temperature that needs to be achieved is dependant on the type of waste as shown in **Table 7-1**. Temperatures in incinerator plant are controlled by the following ways:

- Adjusting the charging rate

  Increasing waste feed will generally increase the temperature in incinerator. However, it should be noted that if the waste feed has low heat content such as pathological waste or very wet waste, the temperature can actually decrease when a charge is added.
- Adjusting the combustion air level

  Automatic air control system functions to limit the temperature increase to the desired temperature setpoint.
- Adjusting the auxiliary burner setpoints

  Auxiliary burner is automatically controlled and activated by temperature setpoints.

Table 7-1: Minimum temperature in secondary chamber required for combustion of waste in incinerator

Type of waste	Minimum temperature, °C
Chemical waste	**850**
Clinical waste	**1000**
Municipal solid waste	**850**
Animal carcasses	**850**
Sewage sludge	**850**
Drum waste	**850**

b. Pressure

Negative pressure must always be maintained in incinerator plant to avoid release of untreated flue gas.

c. Oxygen level

Oxygen level must be maintained above 6% in the secondary chamber to ensure complete combustion. Oxygen level can be monitored using oxygen monitoring system installed at incinerator plant. Types of oxygen sensor are as follow:

- Zirconia sensor
- Paramagnetism
- Low temperature electrochemical cell

d. Residence time

Adequate residence time is vital to ensure efficient combustion. Normally, at least 2 s residence time in secondary combustion chamber is required. Residence time can be determined by dividing volume of secondary chamber to volume of flue gas.

e. Loading rate

High loading rate might cause emission of black smoke. It could also indicate bypass of waste charging system.

7.2.3 Inspection of record keeping

Incinerator plant normally has daily log sheet that records all activities in the plant. Sample of daily log sheet is attached in **Appendix G**. The objectives of record keeping are as follow:

- To comply with statutory and operational conditions requirement
- To indicate premature or potential failure of equipment
- Incease equipment life
- Minimise air pollution
- Provide back up in case of computer failure
- Operative alertness

The items that can be inspected from record keeping are as follow:

a. Waste acceptance

Waste acceptance record shows the amount of waste received, burnt and also the amount of backlog. The amount of waste burnt should not exceed the allowable burning capacity specified by DOE.

b. Ash

Ash record shows the amount of ash generated and the amount sent to Kualiti Alam for disposal. It should be noted that the amount of ash generated should be consistent with mass balance calculations. Significant difference could indicate mishandling of waste or the generated ash.

7.3 Inspection checklist

The checklist for incinerator inspection is shown in **Table 7-2**.

Table 7-2: Inspection checklist for incinerator plant

Inspection	Item	What to look for?	Indication	Comment
Observation	a. Waste bed	Volume of unburned waste	If the volume is rapidly and/or steadily increasing in quantity, it shows that the amount charged is greater than the amount which can be gasified in the same period of time.	
	b. Smoke	Smoke color	Black smoke indicates incomplete combustion of waste due to inadequate oxygen supply. White smoke or plume indicates condensation due to flue gas temperature lower than dew point temperature.	
	c. Noise	Noise level	Simultaneous operation of noise sources results in higher noise level at incinerator plant.	
	d. Ash	Ash quality	Black ash indicates high TOC	
	e. Ducting	Ducting appearance	Ducting that appears to have burn spot and discoloration might indicate damage of insulation or refractory material.	

Inspection	Item	What to look for?	Indication	Comment
	f. Cleanliness	Scattering, breaking or spillage of waste bags	Inefficient implementation of SOP or malfunction of waste charging system.	
Operating parameter	a. Temperature	Minimum temperature as shown in Table 7.1 must be maintained	Temperature might increase due to increasing waste feed. Temperature might reduce if the waste feed has low heat content or very wet waste.	
	b. Pressure	Negative pressure must be maintained	Emission of smoke from incinerator components other than stack indicates negative pressure is not maintained or leaking.	
	c. Oxygen level	Oxygen level must be maintained above 6% in the secondary chamber	Low oxygen level results in inefficient combustion.	
	d. Residence time	Residence time must be at least 2 s	Shorter residence time results in inefficient combustion.	
	e. Loading rate		High loading rate might cause emission of black smoke. It could also indicate bypass of waste charging system	

Inspection	Item	What to look for?	Indication	Comment
Record keeping	a. Waste acceptance	The amount of waste received, burnt and also the amount of backlog.	The amount of waste burnt exceeding the allowable burning capacity shows non compliance with DOE approval.	
	b. Ash	The amount of ash generated and the amount sent to Kualiti Alam for disposal.	Inconsistent in the amount of ash generated with mass balance indicate mishandling of waste or the generated ash. Typical incinerators produce about 3% of fly ash of waste burned.	

TUTORIAL

Mass and Energy Balance Tutorial

The waste characteristics of Kuala Lumpur are given in table below;

Average Waste composition for Kuala Lumpur Municipal Solid Waste

Waste Composition	wt% wet basis	Moisture content, %
Food waste	25.24	70
Paper	13.55	10.2
Cardboard	4.34	5.2
Plastic	17.65	0.2
Textile	2.12	10
Diaper	5.22	85
Rubber	0.65	1.2
Leather	0.20	10
Yard waste	8.55	60
Yard (Fruit husk)	17.74	78.7
Wood waste	1.01	20
Other organic	0.33	-
Glass	2.34	2
Metal	2.38	5
Batteries/Hazardous waste	0.05	-
Other inorganic	0.05	-
TOTAL	100	

Using a basis of 100 tonnes of waste, estimate the following;

i. Amount of air required to incinerate the waste with the excess air level of 8% at the secondary chamber

ii. Volume of flue gas generated at stoichiometric condition

iii. If the residence time required for the secondary combustion chamber is 2 seconds, estimate the flow rate in the secondary chamber

iv. Adiabatic flame temperature of the combustion process

v. Amount of electricity generated

vi. Revenue generated from the sales of electricity

vii. Amount of ash generated

Typical data on the ultimate analysis of the combustible components

Components	Percent by weight (dry basis)					
	Carbon	**Hydrogen**	**Oxygen**	**Nitrogen**	**Sulphur**	**Ash**
Food waste	48	6.4	37.6	2.6	0.4	5.0
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Cardboard	44.5	5.9	44.6	0.3	0.2	5.0
Plastic	60	7.2	22.8	-	-	10.0
Textile	55	6.6	31.2	4.6	0.15	2.5
Diaper	43.5	6.0	44	0.3	0.2	6.0
Rubber	78	10.0	-	2.0	-	10.0
Yard waste	47.8	6.4	38.0	3.4	0.3	4.5
Yard (Fruit husk)	48.5	6.2	39.5	1.4	0.2	4.2
Wood waste	49.5	6.0	42.7	2.6	0.4	5.0
Glass	0.5	0.1	0.4	0.09	-	98.9
Metal	4.5	0.6	4.3	0.09	-	90.5

Note: Discard components with 0.33 wt% (wet) and below

Solution

Average Waste composition for Kuala Lumpur Municipal Solid Waste

Waste Composition	wt% wet basis	Moisture content, %	Dry weight (Tonnes)
Food waste	25.24	70	7.57
Paper	13.55	10.2	12.17
Cardboard	4.34	5.2	4.11
Plastic	17.65	0.2	17.61
Textile	2.12	10	1.91
Diaper	5.22	85	0.78
Rubber	0.65	1.2	0.64
Leather	0.20	10	0.18
Yard waste	8.55	60	3.42
Yard (Fruit husk)	17.74	78.7	3.79
Wood waste	1.01	20	0.81
Other organic	0.33	-	-
Glass	2.34	2	2.29
Metal	2.38	5	2.26
Batteries/Hazardous waste	0.05	-	-
Other inorganic	0.05	-	-
TOTAL	100		57.54

Dry weight = 57.54 tonnes

Moisture content = 42.46 tonnes

Calculation of individual chemical components of the waste stream

Component	Dry weight	C	H	O	N	S	Ash
Food waste	7.57	3.635	0.485	2.847	0.197	0.030	0.379
Paper	12.17	5.293	0.730	5.354	0.037	0.024	0.730
Cardboard	4.11	1.831	0.243	1.835	0.012	0.008	0.206
Plastic	17.61	10.569	1.268	4.016	-	-	1.761
Textile	1.91	1.049	0.126	0.595	0.088	0.003	0.048
Diaper	0.78	0.341	0.047	0.345	0.002	0.002	0.047
Rubber	0.64	0.501	0.064	-	0.013	-	0.064
Yard waste	3.42	1.635	0.219	1.300	0.116	0.010	0.154
Yard (Fruit husk)	3.79	1.833	0.234	1.493	0.053	0.008	0.159
Wood waste	0.81	0.400	0.048	0.345	0.021	0.003	0.040
Glass	2.29	0.011	0.002	0.009	0.002	-	2.268
Metal	2.26	0.102	0.014	0.097	0.002	-	2.046
TOTAL	**57.36**	**27.199**	**3.480**	**18.235**	**0.543**	**0.088**	**7.902**

Sample calculation;

Food waste

$$C = \frac{48}{100} x 7.57 = 3.635$$

$$N = \frac{2.6}{100} x 7.57 = 0.197$$

$$H = \frac{6.4}{100} x 7.57 = 0.485$$

$$S = \frac{0.4}{100} x 7.57 = 0.030$$

$$O = \frac{37.6}{100} x 7.57 = 2.847$$

$$Ash = \frac{5}{100} x 7.57 = 0.379$$

Weight of each component (tones)

Component	**Without H_2O**	**With H_2O**
Carbon	27.199	27.199
Hydrogen	3.480	8.197
Oxygen	18.235	55.977
Nitrogen	0.543	0.543
Sulfur	0.088	0.088
Ash	7.902	7.902

For Hydrogen ➔ with H_2O

$$\left(\frac{2}{18} x 42.46\right) + (3.480) = 8.198 tonne$$

For Oxygen ➔ with H_2O

$$\left(\frac{16}{18} x 42.46\right) + 18.235 = 55.977 tonne$$

Moles of each components; (ash is neglected)

Component	**Atomic weight**	**Without H_2O**	**With H_2O**
Carbon	12.01	2.265	2.265
Hydrogen	1.01	3.446	8.117
Oxygen	16.00	1.140	3.498
Nitrogen	14.01	0.039	0.039
Sulfur	32.07	0.003	0.003

Sample Calculation;

Carbon ➔ without H_2O

$$\frac{27.199}{12.01} = 2.265 mol$$

with H_2O

$$\frac{27.199}{12.01} = 2.265 mol$$

Mole ratio, C = 1

Component	**Without H_2O**	**With H_2O**
Carbon	1.000	1.000
Hydrogen	1.521	3.584
Oxygen	0.503	1.544
Nitrogen	0.017	0.017
Sulfur	0.001	0.001

Sample calculation; (without H_2O)

$$\text{Carbon} = \frac{2.265}{2.265} = 1.000$$

$$\text{Hydrogen} = \frac{3.446}{2.265} = 1.521$$

$$\text{Oxygen} = \frac{1.140}{2.265} = 0.503$$

$$\text{Nitrogen} = \frac{0.039}{2.265} = 0.017$$

$$\text{Sulfur} = \frac{0.003}{2.265} = 0.001$$

with H_2O

$$\text{Carbon} = \frac{2.265}{2.265} = 1.000$$

$$\text{Hydrogen} = \frac{8.117}{2.265} = 3.584$$

$$\text{Oxygen} = \frac{3.498}{2.265} = 1.544$$

$$\text{Nitrogen} = \frac{0.039}{2.265} = 0.017$$

$$\text{Sulfur} = \frac{0.003}{2.265} = 0.001$$

Empirical Formula, without water = $CH_{1.521}O_{0.503}N_{0.017}S_{0.001}$

Empirical Formula, with water = $CH_{3.584}O_{1.544}N_{0.017}S_{0.001}$

i) Amount of air required to incinerate the waste with the excess air level of 8%

Solution

$CH_{3.584}O_{1.544}N_{0.017}S_{0.001} + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dSO_2 + eN_2$

C: $b = 1$

H: $2c = 3.584$ $c = 3.584/2 = 1.792$

O: $2b + c + 2d = 1.544 + 2a$

N: $2e = 0.017 + 7.52a$

S: $d = 1$

Solve for a, b, c, d and e yields;

$a = 2.124$ $b = 1$ $c = 1.792$ $d = 1$ $e = 7.995$

Therefore, the stoichiometric combustion equation;

$CH_{3.584}O_{1.544}N_{0.017}S_{0.001} + 2.124(O_2 + 3.76N_2) \rightarrow CO_2 + 1.792H_2O + SO_2 + 7.995N_2$

Thus;

1 mol fuel = 2.124 mol O_2 (at stoichiometric)

= or 1.08 x 2.124 = 2.294 mol O_2 (at 8% excess air)

1 mol fuel = 2.124 mol O_2 x $(0.79N_2)/(0.21O_2)$

1 mol fuel = 7.986 mol N_2

Thus,

Total mol of air = $2.124O_2 + 7.989N_2$ = 10.110 mol of air

So,

1 mol of fuel = 10.110 mol of air at stoichiometric

(8% excess air) x 1.08 10.110 = 10.919 mole of air feed

1 mol fuel = 40.558 g/mol x 1 mol of fuel = 40.558 g

10.110 mol of air = 29 g/mol x 10 mol of air = 293 g

8% excess air = 1.08 x 293 g = 316.44 g of air

ii) Volume of flue gas generated

Assume ideal gas law, P = 1 atm, T = 298K

PV = nRT

Total moles of flue gas generated at stoichiometric condition;

$N_T = 1 + 1.792 + 1 + 7.995 = 11.787$ moles

$V = nRT/P$

$= (11.787\ \text{mol})(0.08206\text{L.atm/mol.K})(298\text{K})/1\text{atm}$

$= 288$ Litre $= 0.288\text{m}^3$

iii) If the residence time required for the secondary combustion chamber is 2 seconds, estimate the size of the secondary chamber

t = 2s   Volume, $V = 0.288\text{m}^3$ Q =Flow rate, m^3/s

t = V/Q

$Q = \text{m}^3/\text{s} = 0.288\ \text{m}^3/2\text{s} = 0.144\ \text{m}^3/\text{s}$

iv) Adiabatic flame temperature of the combustion process

Stoichiometric reaction;

$CH_{3.584}O_{1.544}N_{0.017}S_{0.001} + 2.124(O_2 + 3.76N_2) \rightarrow CO_2 + 1.792H_2O + SO_2 + 7.995N_2$

Oxygen fed (at 8% excess air) = 1.08 (2.124 mole) = 2.294 mol O_2

Excess oxygen = 2.294 mole – 2.124 mole = 0.17 mol O_2

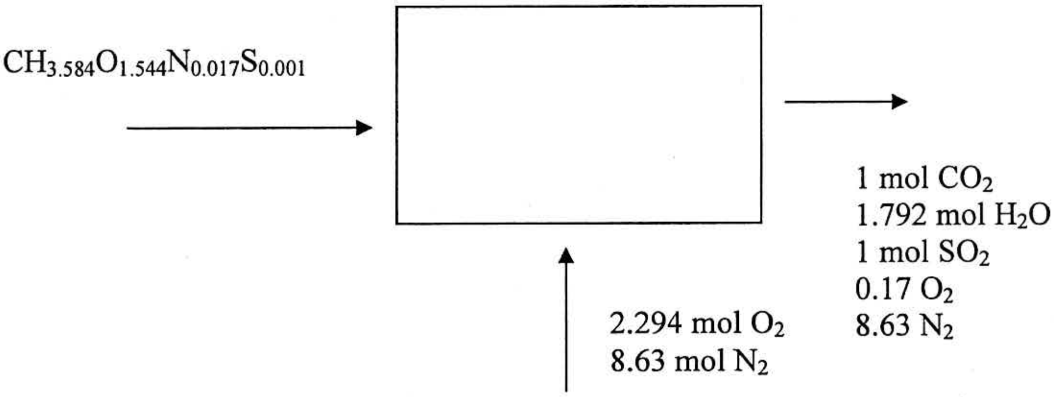
Total mole air fed $= \dfrac{2.294}{0.21} = 10.924$ mol air @ 10.913 as in solution Q1

Nitrogen fed = (10.924 – 2.2294)mol = 8.63 mol N_2

→ air = nitrogen + oxygen

At excess air (8%)

$CH_{3.584}O_{1.544}N_{0.017}S_{0.001} + 2.294O_2 + 8.63N_2 \rightarrow CO_2 + 1.792H_2O + SO_2 + 8.63N_2$



The energy balance is used to calculate the adiabatic flame temperature, T_{ad}

The equation is as follows;

$$\Sigma\, ni\, \hat{H}i\, (Tad) = -nf\, \Delta\hat{H}c + \Sigma\, ni\, \hat{H}i\, (Tfeed)$$

To calculate the right hand side of the equation; (inlet)

$-n_f \Delta\hat{H}_c$ = (1 mole of waste) X Molecular weight of waste X LHV

= 1 mol X 40.558 g/mol X 10230 J/g

= 414.908 kJ

$\Sigma n_i \hat{H}_i$ (T feed) = $H_{\text{solid waste}}$ at 25^0C + H_{air} at 800^0C

= 0 + (10.924 mol of air)(24.1 KJ/mol)

= 263.268 kJ

Total enthalpy of right hand side of the equation

= 678.176 kJ

To calculate the left hand side of the equation;

$$\Sigma n_i \hat{H}_i (Tad) = n_{H_2O(v)}(H_v) + \int_{25^0 C}^{Tad} \sum n_i CpdT$$

Thus;

$$= (1.792 \text{ mol})(44.013\text{kJ/mol}) + \int_{25^0 C}^{Tad} \sum n_i CpdT$$

$$= 78.871 \text{ kJ} + \int_{25^0 C}^{Tad} \sum n_i CpdT$$

Enthalpy of the product stream is determined from Felder and Rousseau, Table B2

Component	Mole	A	B	C	D
CO_2	1.000	3.6110×10^{-2}	4.2330×10^{-5}	-2.8870×10^{-8}	7.4640×10^{-12}
H_2O	1.792	3.3460×10^{-2}	6.8800×10^{-6}	7.6040×10^{-9}	-3.5930×10^{-12}
SO_2	1.000	3.8910×10^{-2}	3.9040×10^{-5}	-3.1040×10^{-8}	8.6060×10^{-12}
O_2	0.170	2.9100×10^{-2}	1.1580×10^{-5}	-6.0760×10^{-9}	1.3110×10^{-12}
N_2	8.630	2.9000×10^{-2}	2.1990×10^{-6}	5.7230×10^{-9}	-2.8710×10^{-12}
Total		3.9020×10^{-1}	1.1464×10^{-4}	2.0729×10^{-9}	-1.4923×10^{-11}

$Cp = A + B(T) + C(T^2) + D(T^3)$, T in °C

Thus;

$$\sum n_i Cp = 3.9020X10^{-1} + 1.1464X10^{-4}T + 2.0729X10^{-9}T^2 - 1.4923X10^{-11}T^3$$

Thus,

Σ ni $\hat{H}$i (Tad) = 78.871 kJ +

$$\int_{25^0 C}^{Tad} 3.9020X10^{-1} + 1.1464X10^{-4}T + 2.0729X10^{-9}T^2 - 1.4923X10^{-11}T^3$$

From the energy balance equation and for the adiabatic process, $\Delta H = 0$

Σ ni $\hat{H}$i (Tad) = -nf $\Delta\hat{H}$c + Σ ni $\hat{H}$i (Tfeed)

ΔH = 414.908 kJ + 263.268 kJ - 78.871 kJ +

$$\int_{25^0 C}^{Tad} 3.9020X10^{-1} + 1.1464X10^{-4}T + 2.0729X10^{-9}T^2 - 1.4923X10^{-11}T^3$$

Integrating the integral function and solve the equation by trial and error yield;

$T_{ad} = 1333.45^0C$

v) Amount of electricity generated

Chemical formula of waste; $CH_{1.521}O_{0.503}N_{0.017}S_{0.001}$

Energy content of waste; (dry basis)

Component	No of atoms per mole	Atomic weight	Weight contribution	Percent (%)
Carbon	1	12.01	12.01	54.930
Hydrogen	1.521	1.01	1.536	7.024
Oxygen	0.503	16.00	8.048	36.805
Nitrogen	0.017	14.01	0.238	1.089
Sulfur	0.001	32.07	0.032	0.146
		TOTAL	21.864	100.00

Use Dulong equation to estimate the energy content; (dry basis)

$$33801\ (C) + 144158\ [(H) - 0.125\ (O)] + 9413\ (S)$$

Dry basis

HHV (kJ/kg) $= 33801\ (C) + 144158\ [(H) - 0.125\ (O)] + 9413\ (S)$

$= 33801\ (0.549) + 144158\ [(0.070) - 0.125(0.368)] + 9413(1.46\text{x}10^{-3})$

= 22030 kJ/kg

= 22.03 MJ/kg

LHV (kJ/kg) = HHV – heat of vaporization of water at 25^0C

= 22.03 MJ/kg – 2.445 MJ/kg

= 19.585 MJ/kg

Wet Basis (as received)

HHV = 22.03 MJ/kg x (100 – moisture content)/100

= 22.03 MJ/kg x (100 – 42.46)/100

= 12.67 MJ/kg

LHV = HHV – heat of vaporization of water at 25^0C

= 12.67 MJ/kg – 2.445MJ/kg

= 10.23 MJ/kg

Heat released;

$$10.23\frac{MJ}{kg}x\frac{100tons}{day}x\frac{1000kg}{1ton}x\frac{1day}{24hr}x\frac{1hr}{3600s}=11.84\frac{MJ}{s}=11.84MW$$

Electricity generated; (assume 20% plant efficiency);

= 0.2 x 11.84MW = 2.37 MW

vi Revenue generated from the sales of electricity

Assume, 1 kWhr = RM0.20

$$2.37MWx\frac{1000kW}{1MW}x\frac{0.20RM}{1kWhr}x\frac{24hr}{1day}$$

= RM11376/day

vii. Amount of ash generated

Component	**Tonnes/day**
Combustible	49.55
Noncombustible	7.902
Water	42.46
Total	100

Amount of ash generated = 7.902 tonnes/day

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