

Chapter 6

Combustion and Incineration



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Abstract In several countries worldwide, combustion and incineration are the second main option for waste management and disposal. There are different types of incineration systems on the market. This chapter examines the method of urban solid waste mass-burn incineration, from waste collection to bunker and feeding systems, furnaces, and heat recovery systems. Fluidised bed incinerators, starved air incinerators, rotary kiln incinerators, cement kilns, liquid and gaseous waste incinerators, and the waste types incinerated in the various incinerators are also addressed. Particulate matter, heavy metals, toxic and corrosive gases, and incomplete combustion products such as polycyclic aromatic hydrocarbons (PAHs), dioxins, and furans are discussed, as well as pollution creation and control. The wastewater, bottom ash, and fly ash generated by waste incineration are all addressed. The emission dispersion from the chimney stack is defined. The waste-to-energy (WtE) part of incineration is also presented. There are also several case studies mentioned.

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Acronyms

BAT	Best Available Technique (or Best Available Technology, used in the United States)
BREF	Best Available Technique Reference Document
CAR	Clean Air Regulation
Cd	cadmium
CO	carbon monoxide
CO ₂	carbon dioxide
DOE	Department of Environment
DRE	destruction and removal efficiency
ESP	electrostatic precipitator
FGT	flue gas treatment
HCl	hydrogen chloride
HF	hydrogen fluoride
ICRF	inductively coupled radio frequency
IPPC	Integrated Pollution Prevention Control
MSW	municipal solid waste
MSWI	municipal solid waste incinerator
NO _x	nitrogen oxides
N ₂ O	nitrous oxide
ODS	ozone-depleting substances
PCBs	polychlorinated biphenyls
SCR	Selective catalytic reduction
SO _x	sulphur oxide
SO ₂	sulphur dioxide
TOC	total organic carbon
VOC	volatile organic compound
WM	waste management
WtE	waste-to-energy

Nomenclature

Δh	enthalpy change
ρ	instantaneous density (g/cm ³)
d_o	particle of initial diameter
f_{CO}	mole fractions of CO
f_{O_2}	mole fractions of O ₂
f_{H_2O}	mole fractions of water vapor
k_s	kinetic rate constant for the consumption reaction

k_d	diffusional rate constant
K_p	equilibrium constant
$M C_p^0$	molar heat capacity ($\text{kcal mol}^{-1} \text{ }^\circ\text{C}^{-1}$)
$M C_{p,avg}^0$	average molar heat capacity ($\text{kcal mol}^{-1} \text{ }^\circ\text{C}^{-1}$)
P	absolute pressure (atm)
q	rate of carbon consumption ($\text{g cm}^{-2} \text{ S}^{-1}$) t
R	universal gas for ideal gases
T	absolute temperature (K)
V	volume (m^3)

6.1 Introduction

In solid waste management schemes, one of the solutions is incineration. It is a mechanism in which combustible waste is combusted, incinerated, or oxidised, producing carbon monoxide (CO), hydrogen chloride (HCl), hydrogen fluoride (HF), nitrogen oxides (NO_x), sulphur dioxide (SO₂), the volatile organic compound (VOC), dioxins and furans, polychlorinated biphenyls (PCBs), heavy metals, and other by-products. As shown in Fig. 6.1, the entire process involves the waste passing through the distribution system, the bunker and feeding system, the boiler, heat recovery systems, and the gas cleaning system, with ash as the end product [1]. This method is appealing because it can dramatically reduce waste volume by up to 80–90% [2] and weight by up to one-third of its pre-burnt weight [3, 4]. It cannot,

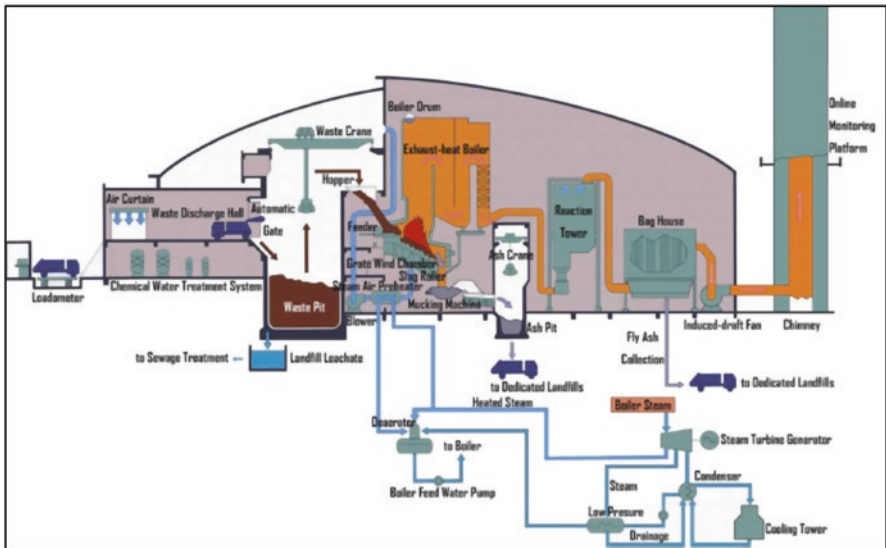


Fig. 6.1 Schematic of a typical solid waste incinerator [1]

however, be a stand-alone operation because its ash or solid residue must be landfilled.

Incineration is also the most practical choice for certain wastes that are too dangerous or expensive to recycle or landfill safely, such as highly flammable materials and radioactive or infectious waste [4]. Furthermore, the energy obtained from waste incineration may be used to generate steam for electricity generation, industrial process heating, or hot water for district heating, thus conserving valuable primary fuel resources [3, 5]. In addition, incinerator bottom ash, a by-product of incineration, may be collected and re-used as secondary aggregates in the building [6].

Incineration, on the other hand, has its own set of drawbacks. The most notable disadvantage is that it has a very high capital cost and a longer payback period [7]. Other disadvantages include operating problems caused by the refuse character, process sophistication, and negative public reactions to the process [8].

However, the benefits of incineration greatly outweigh the drawbacks, and incineration is now accepted as the best environmentally friendly alternative for MSW disposal. The public understanding of the health and environmental risks posed by landfill has resulted in the closure of many landfill sites around the world. In the United States, for example, the figure was over 6,000 in 1990, but by 2017, it had fallen to just 1,270 [9]. Another aspect that favours incineration over landfill disposal is the rising cost of landfill disposal, which includes rises in landfill tax and transportation costs. The landfill tax in the United Kingdom was £7.00 per tonne in 1992, raised to £10.00 per tonne in 1999 [10], and will be £96.70 [11] per tonne in 2021. Thus, the future of waste incineration will be determined by the availability of landfills near densely populated areas, the amount of energy recovered by incinerators, and the extremely high capital and operating costs of incinerator plants [7].

6.2 Municipal Solid Waste Incinerator Plant

6.2.1 Background

In the United Kingdom, the first incinerator was constructed in Paddington City in 1870, while the first MSW incinerator without energy recovery in the United States was installed in New York City in 1885 [12]. However, it was closed due to complaints by the public of smell and smoke production [12]. Another incinerator was built in Manchester in 1876 [13]. It was a cell furnace with batch-wise combustion, in which the waste was manually loaded, and the ash was removed at the high furnace temperature. Many more incinerators have been built since then, but many of them were closed due to fundamental design flaws. As incineration technology improved with provisions for cleaner and efficient combustion, the traditional cell-furnace design was replaced by the shaft-furnace design, and the batch-wise combustion was replaced by continuous combustion using moving grate systems with a

capacity between 10 and 50 tonnes per hour [14]. As a result, only moving grate systems are explored in depth in this chapter. A brief description of a smaller incinerator with a waste capacity of 1 to 2 tonnes per hour, such as clinical waste, sewage sludge, and hazardous waste, is given [4]. Typical examples of such devices include fluidised bed, cyclonic, starved air or pyrolytic, rotary kiln, rocking kiln, cement kiln, and liquid and gaseous incinerators.

In general, an incinerator process can be broken down into a few parts, as defined in the previous section: waste delivery, bunker, and feeding systems, furnace systems, heat recovery systems, and gas cleaning systems. Each section of an incinerator will be described in the subsections that follow (please refer to Fig. 6.1).

6.2.2 Waste Delivery, Bunker, and Feeding System

The waste is unloaded and stored in a waste bunker when waste collection vehicles arrive at an MSWI plant. The bunker should be wide enough to hold around 2–3 days' worth of waste equivalent in weight, which will be about 1000–3000 tonnes of waste, to ensure a balance between an uneven waste distribution and the plant's continuous activity [4]. The bunker in some incinerator plants is divided into parts to isolate waste with different calorific values and combustion properties. Until loading them into the feeding hopper, the crane operator can combine them. The crane operator would also remove any bulky or hazardous objects from the refuse for further processing. The waste is then loaded into the feeding machine by the operator. The crane grab has a waste capacity of 6 m³.

The waste in the steel hopper will flow into the incinerator under its own weight in the feeding device. The material is then conveyed into the grate system through a hydraulic pump or other means. To prevent air leakage into the furnace and ensure uninterrupted feed to the grate, the hoppers are held partially stuffed with waste. A monitor is used to calculate the amount of waste. The furnace entrance is sealed by hydraulic shutters to prevent the fire inside the furnace from spreading to the feeding hopper. The feed chute may also be water-cooled or lined with refractory material.

6.2.3 Furnace System

This is the section where solid waste is incinerated. Commonly, the number of furnaces depends on the capacity of the incinerator, with each furnace having the capacity to burn 10 tonnes/hour of waste [4]. Thus, a typical 60 tonnes/hour incinerator would have six furnaces. The advantage of having multiple furnaces is that if one furnace needs repair, the others can still be operated, which limits its downtime.

Generally, the furnace consisted of a moving grate and incineration chamber. The movement of waste inside this furnace is helped by the individual action of the

grate. The primary air is pumped from under the grate, and the secondary air is pumped from just above the waste bed before the radiation shaft. As the solid waste whose orientation differ in size, shape and orientation is transported from the feed input to the ash end of the incinerator through the grate, it will undergo the processes of drying; pyrolysis; solid and gas phase combustion; conductive, convective and radiative heat transfer; and mass transfer. Since the waste stream components differ in moisture content, thermal degradation temperature, volatile composition and ignition temperature, and fixed carbon content, the stages converge in practice [4].

As the raw, wet waste is fed onto the grate, it is initially dried by the heat radiated from the overbed region and from the burning waste. The injection of pre-heated primary air also assists the drying process. At temperature between 50–100°C (373 K), the waste loses most of its moisture content. The amount of water in waste is important because heat is required to evaporate it, which means that more of the waste's usable calorific value is lost in the process of heating up the wet waste, resulting in less energy available. Furthermore, the amount of water in the waste will affect the rate of heating and thus the rate of thermal decomposition. The water content of municipal solid waste can range anywhere from 25% to 60%.

After the moisture is released, the temperature rises to about 260 °C (533 K), and the thermal decomposition and pyrolysis of organic materials such as paper, plastics, food waste, textiles, and so on begins. VOCs, combustible gases, and vapours are produced as a result of the processes. The typical amount of VOC in MSW is between 70% and 90%, and they are formed as hydrogen (H₂), carbon monoxide (CO), methane (CH₄), ethane (C₂H₆), and other higher molecular weight hydrocarbons [4].

In general, waste ignition begins around 316°C (589 K). The waste is then burned above the waste on the grate and in the combustion chamber above the grate until all of the oxygen is consumed, or all of the waste has devolatilised to carbonaceous char. To ensure good mixing and complete combustion of the gases and vapours, a sufficiently high temperature, adequate residence time, and excess turbulent air are needed. Devolatilisation occurs over a temperature range of 200–750 °C, with 425 and 550 °C being the primary release of VOCs. Furthermore, the release of VOCs is affected by the different components present in the waste.

Polystyrene, for example, decomposes at temperatures between 450 and 500°C, yielding approximately 100% volatiles, while wood decomposes at temperatures between 280 and 500°C, yielding roughly 70% volatiles [4]. The rate of thermal decomposition can also be affected by the waste's structure and physical condition. Cellulosic material in thin form, such as paper, decomposes in seconds, while cellulosic material in the form of a large piece of wood will take several minutes to decompose fully.

Since the furnace gas temperature is usually between 750 and 1000 °C but can reach temperatures as high as 1600 °C, the volatile gases and vapours emitted instantly ignite in the furnace. The residual char or partially charred waste can be pyrolysed further, gasified by CO₂ or H₂O to produce CO and H₂, or oxidised by O₂ to produce CO₂, with the ash remaining in the bed at the end of the process. Since

MSW is heterogeneous in nature and the waste elements next to it differ in size and composition, the processes of drying, pyrolysis, and gasification of the waste can occur concurrently in the burning bed.

From the beginning, secondary air is supplied through nozzles above the grate to ensure that there is enough air for combustion and to create turbulence [4]. Excess secondary air is needed to avoid areas where there is no oxygen, which causes the hydrocarbons to pyrolyse rather than burn, potentially resulting in hazardous high molecular weight hydrocarbons and soot. As a result, secondary air circulation and turbulence characteristics play an important role in reducing pollutant formation in the combustion chamber.

From the above, it is stipulated that to design an incinerator plant, a good combination of mechanical and chemical engineering knowledge plays an important role in ensuring that the movement of waste is uninterrupted and combustion is as complete as possible to reduce hazardous emission. The following subsection describes the types of moving grates available in the market.

6.2.3.1 Travelling Grate

As shown in Fig. 6.2, the travelling grate is normally made up of two or more continuous metal-belt conveyors [15]. The waste from the hopper is sent to the first grate. The waste is dried here before starting to volatilise and burn, eventually falling onto the second grate, also known as the burning grate. The bottom ash from the incineration process is collected in an ash hopper at the end of the burning grate.

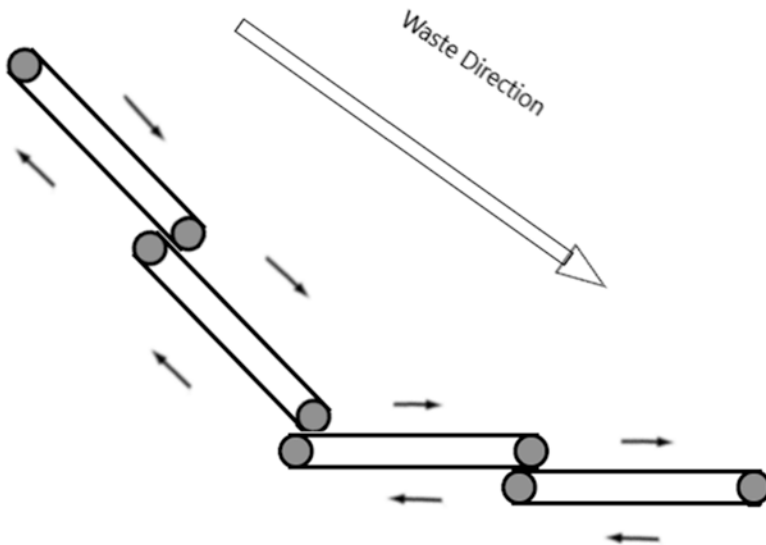


Fig. 6.2 Travelling grate

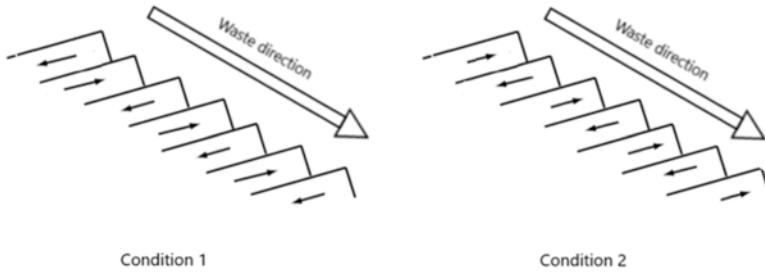


Fig. 6.3 Double motion grate [16]

This system is reliable and relatively cheap. On the other hand, a disadvantage of this system is that the waste does not experience any form of mixing or agitation in the process. The only disturbance to the waste is when it falls from one grate to another, which results in poor waste mixing during combustion. This type of grate thus requires a large amount of air to be provided to improve combustion and consequently produces an extremely large volume of flue gas that needs to be treated. As a result, the particulate removal system can become overloaded, causing high particulate emissions.

6.2.3.2 Double Motion Overthrust Grate

A double motion overthrust grate is shown in Fig. 6.3 [16]. The term “double motion” refers to the arrangement of rows of moving grate bars in opposite directions that are superimposed. When the grate bars adjacent to a stationary bar move away from each other, the grate bars adjacent to the next stationary bar move in the opposite direction. The horizontal structure of the grate, as well as the continuous movement of the rows, enables the waste to be advanced in a controlled manner while preventing sliding. The waste layer loosens as the grate bars move away from each other, and the waste is moved to the next section of the grate before finally falling into the space created by the moving grate bars.

6.2.3.3 Reciprocating Grate

As shown in Fig. 6.4, the reciprocating grate is made up of a series of steps with moving and fixed grate parts angled downwards towards the ash discharge trap. The shifting grates slide back and forth between the stationary grates, agitating and transferring the waste to the ash hopper. The reciprocating grate can also be set up in a multiple-level sequence to provide more agitation to the bed. This grate is ideal for burning wet refuse because it has excellent primary air distribution, resulting in a high-quality burn-out [18]. The biggest drawback of this grate, however, is the bad waste mixing.

Fig. 6.4 Reciprocating grate

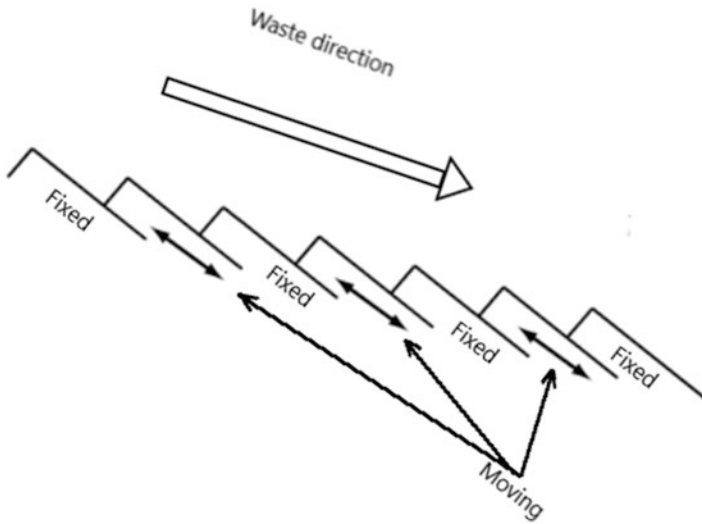
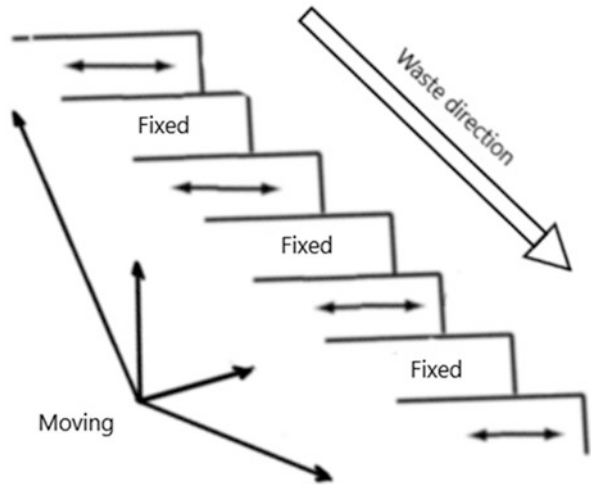


Fig. 6.5 Reverse acting reciprocating grate

6.2.3.4 Reverse Acting Reciprocating Grate

The reverse acting reciprocating grate, like the reciprocating grate mentioned above, is made up of a stack of stepwise configured moving and fixed grate parts that are angled downwards with a steeper angle towards the discharge end, as shown in Fig. 6.5. The key difference being that the grate components reciprocate upwards to the waste’s downward progress, allowing the burning content to roll due to the upward reverse thrust. The grate’s steplike design provides additional mixing as the waste tumbles from one stage to the next. The reverse acting reciprocating grate has

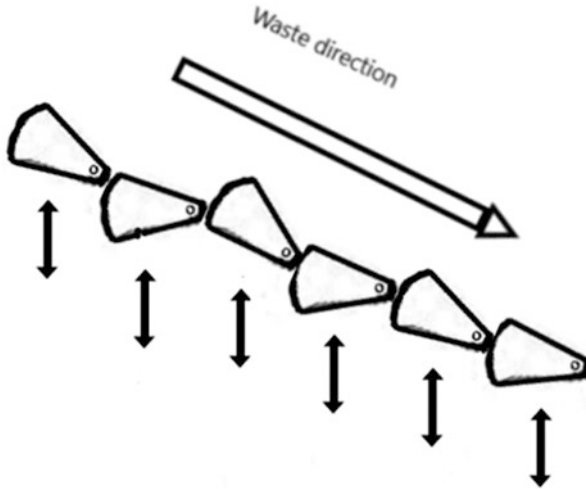


Fig. 6.6 Rocking grate

the advantages of being very effective, producing good burn-out, and being able to manage long operating hours. It is, however, a costly grate with high maintenance costs. Small items being trapped between the grate bars is a common issue with this form of the grate. The Martin reverse-acting reciprocating grate is one of the devices that use the reciprocating grate [19].

6.2.3.5 Rocking Grate

A rocking grate is designed to slope downwards towards the ash discharge end, as shown in Fig. 6.6. It is usually made up of two or three grate parts that are the same width as the furnace. Alternate grate rows are rotated 90 degrees forward around the axis to achieve an upward and forward motion. This movement causes the waste to agitate and step forward. While the alternating grate rows rotate forward, these grates rotate back to their original resting positions. The waste is agitated and pushed forward by the constant back-and-forth movement of alternate grates. This grate is well-known for producing excellent burn-out. It does, however, have drawbacks in that small items may get stuck between the grates, necessitating regular operational maintenance, and in some cases, weekly maintenance. The Esslingen and Nichols systems are two examples of rocking grate systems [4].

6.2.3.6 Roller Grate

This type of grate was developed in the West Germany city of Düsseldorf in 1965 to counteract the high cost of multiple travelling grates. The roller grate is made up of a set of slotted rotating drums, as shown in Fig. 6.7. Each drum rotates forward,

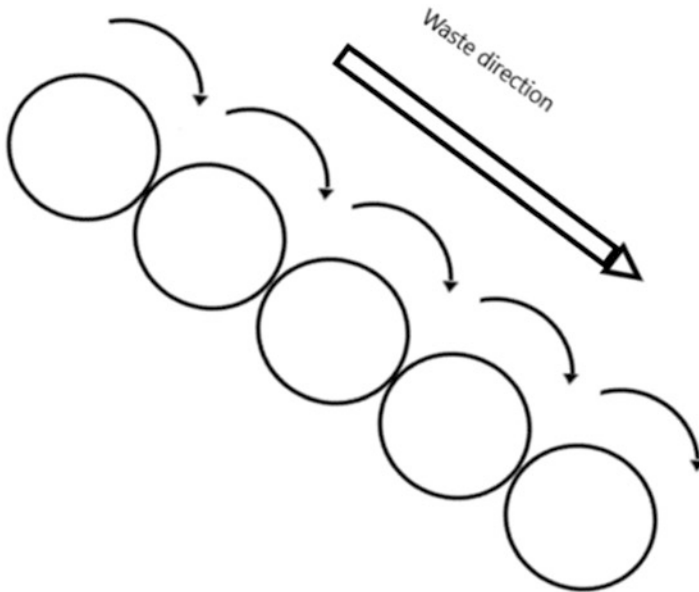


Fig. 6.7 Roller grate

agitating and transporting the waste to the next. The waste is often mixed between the drums as they rotate. Each drum spans the entire width of the furnace and has its own variable speed control, allowing for better grate control during combustion than other grate forms [20]. The major drawback of this grate is that small objects can get stuck between the drums and cause them to stop rotating. The roller grate is exemplified by the Düsseldorf WtE method.

6.2.3.7 Incineration Chamber

The waste's volatile compounds are burned in the combustion chamber, which is situated above the grate. The shapes are to be considered. They are very important as they influence combustion efficiency. The mean residence time of the gaseous volatiles is determined by the size of this chamber, while the form influences the heating pattern of the incoming waste, which receives heat from both the hot flue gases and the furnace wall. Furthermore, the shape of the chamber has an effect on the gaseous flow pattern within it, which affects recirculation and mixing. As shown in Fig. 6.8, the two most common types of combustion chambers are shown.

Vertical shaft combustion chambers are sometimes combined with reverse reciprocating or roller grates. Its architecture allows for efficient gas mixing as well as a long gas residence period. However, the combustion air distribution affects its output. As shown in Fig. 6.8, there are three types of vertical shaft combustion chambers in use today: parallel gas flow designs, contra gas flow designs, and centre gas

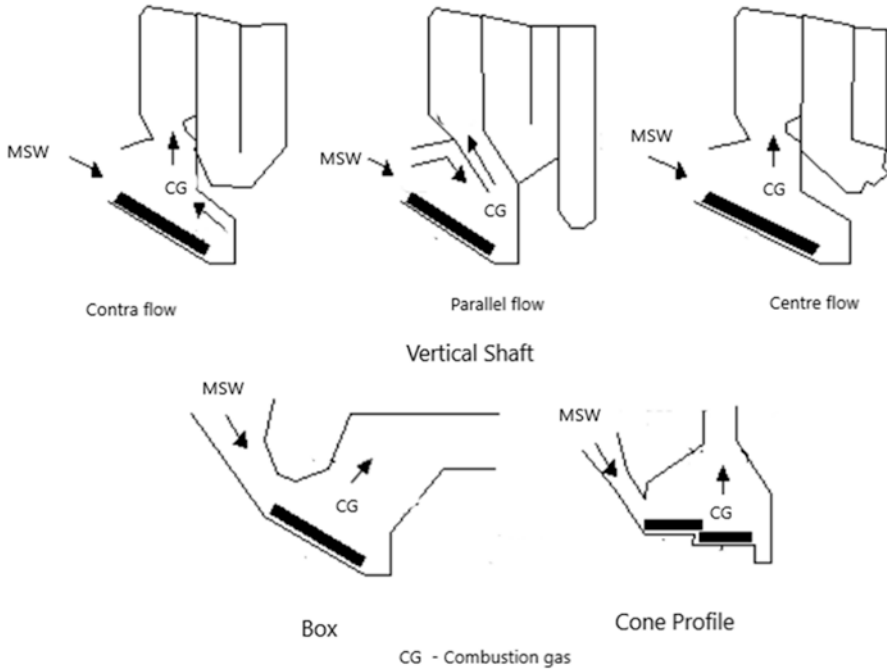


Fig. 6.8 Types of incineration chamber

flow designs. The contra gas flow form is appropriate for wastes that are difficult to burn, such as those with a high moisture content or low volatility [17]. The parallel flow style, on the other hand, favours dry, easily ignited waste [17]. The features of the first two designs are combined in the centre gas flow version.

The rocker and W-grate plants are often combined with the box form of the combustion chamber. As shown in Fig. 6.8, its shape is a variant of a rectangular box that is slightly longer and lower. The downside of this type of combustion chamber is that, due to poor combustion air distribution, its gas turbulence is not as strong as the vertical shaft type.

As shown in Fig. 6.8, the cone profile style combustion chamber is normally used in conjunction with an L-stoker grate. Its architecture does not allow for a long stay. To protect the combustion chamber walls from thermal stresses or deterioration due to high-temperature corrosion and abrasion, they are coated with refractory material. Furthermore, the refractory material emits heat to speed up the drying process, which is then accompanied by the ignition and combustion of the incoming waste. The type of refractory material used is determined by the combustion chamber's predicted strength of combustion [22].

The unburnt gaseous volatiles emerging from the waste bed are first mixed with the secondary air and subsequently burnt. Hot combustion products flow through the radiation shaft to the heat recovery section of an incinerator, as shown in Fig. 6.1.

6.2.4 Enclosure

The enclosure that surrounds the grate framework is an essential part of the overall system design. The hot enclosure surfaces not only contain the fuel, but they also radiate heat to the incoming feed, speeding up the drying and combustion of refuse. Furthermore, the shape of the enclosure influences the flow patterns of combustion gases. Furnace enclosures can be made of refractory material or of a “Waterwall furnace,” which is made up of a series of water-filled boiler tubes linked by a short metal bridge. At the grating line, refractory material (usually silicon carbide for its abrasion resistance and high thermal conductivity) is often installed, typically reaching one to three meters above the grate in either case.

6.2.5 Heat Recovery Systems

Incineration is an extensive heat-generating process. Most of the heat from the incineration process is transferred as flue gases. In a modern incinerator where there is a flue gas treatment system, this high-temperature flue gas, which is usually around 750–1000 °C must be cooled to below 250–300 °C before it can be passed through a flue gas treatment system usually consisted of such as electrostatic precipitators, scrubbers, and bag filters. This process can be achieved through the insertion of a system of boiler tubes at a separate boiler chamber with a specified configuration [5]. Fig. 6.9 shows the plant configuration of the heat recovery system

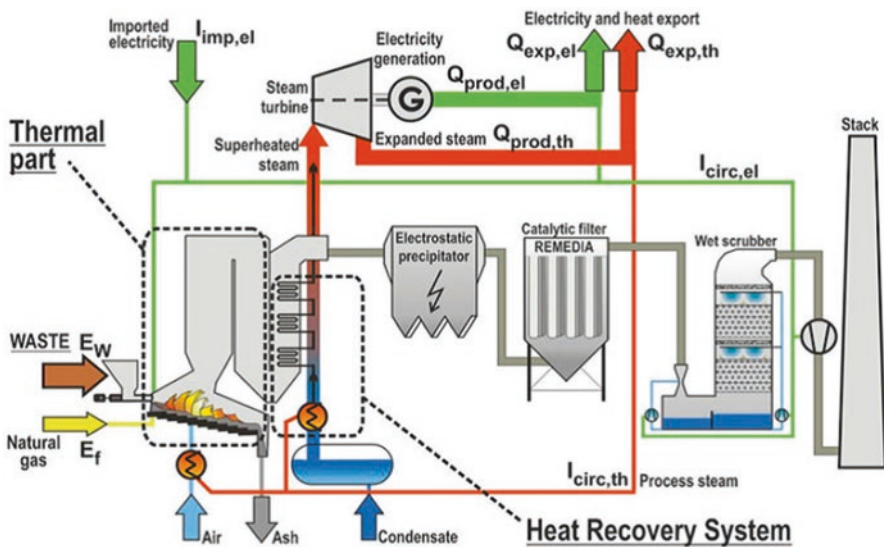


Fig. 6.9 Plant configuration of heat recovery system [21]

[21]. During the cooling process, this boiler device recovers thermal energy by collecting radiant heat from the combustion zone as well as the hot flue gas. Depending on the composition, moisture level, and local activities, this heat content typically ranges from about 2500 kcal/kg [22]. The concentrated heat is used to heat water in a tube bank, resulting in extremely hot steam in the boiler tubes. As a result, this steam is directed to a steam turbine, which generates electricity. Furthermore, hot steam may be used for district heating or for power and space heating inside the plant. The quality of steam is generally determined by temperature, friction, and the water-steam cycle. The natural temperature and pressure are currently around 400°C and 4 MPa, respectively [23]. WtE incineration devices, on the other hand, cannot be equipped for high-temperature and high-pressure systems like power plants because the flue gas contains corrosive gases like hydrogen chloride.

Fouling of the tubes by flue gas deposits, which include fly ash, soot, volatilised metal compounds, and other pollutants, is a major factor in the boiler's performance [4]. The deposits stick to the boiler tubes, limiting heat transfer from the hot flue gases to the water in the steel tubes, lowering steam output, and lowering energy recovery [5]. Flue gas dust filling, fly ash stickiness, which is determined by temperature, flue gas velocity, and tube bank geometry all influence the rate at which tube fouling deposits form. The boiler tubes should be positioned parallel to the gas flow to avoid fouling and corrosion. The presence of molten salts such as calcium, magnesium, and sodium, as well as sulphates, oxides, bisulphates, chlorides, pyrosulphates, and other compounds in the fly ash, as well as SO₃ and HCl, determines the adherence of fly ash to boiler tubes [4]. Soot blowers (which use superheated steam) and shot cleaning (which involves dropping a cast-iron shot on the tubes to shake off the deposits) will also help remove scale deposits (rapping the tube banks to knock off the deposits). Soot blowers are the most common, and they are typically used only once per operational shift. The boiler must be shut down for a thorough mechanical or wet cleaning after 4000 hours of operation when the flue gas outlet temperature reaches a set level [5].

When designing and running incinerator boilers, corrosion is another important factor to remember [5]. Low-temperature acid corrosion can be caused by the formation of HCl from the combustion of chlorine-containing wastes like paper and board, as well as plastics like PVC. At both high and low temperatures, temperature control is critical for avoiding corrosion in the boiler. A series of chemical reactions between tube metal, tube scale deposits, slag deposits, and flue gases in superheater boiler tubes in the boiler chamber at temperatures greater than 450°C causes high-temperature corrosion. Temperature, the presence of low melting phases such as alkali bisulphates and pyrosulphates, acid gases such as HCl and SO₃, the presence of the tube metal, and the frequency of reducing conditions all affect the rate of corrosion. Acid gases such as HCl and H₂SO₄ condense as the temperature drops below the dew point, causing low-temperature corrosion.

As of 2013, the WtE industry is estimated to be worth approximately USD 24 billion [24] and is expected to reach USD 37.6 million by 2020 [25]. As of 2014, at least 80 WtE incinerators were operational in the United States, generating 2769 MWh daily [26]. Many other countries such as Denmark, Sweden, Estonia, Finland, and Japan incinerate at least 50% of their MSW for power generation [27].

Table 6.1 Emission limits for selected countries [28]

Country	Germany -90 Law	UK HMIP IPR 5/3	Sweden -87 Guidelines C ≥ 250 tpd	Netherlands-89 Law New plants	USA-91 Proposal New plants	EC Directives -89, O ₂ = 11% New plants C > 5 ton/h
Average	Day	Hourly	Month	Month		Week
	11% O ₂ dry	11% O ₂ dry	10% CO ₂ dry	11% O ₂ STP dry	7% O ₂ dry	11% O ₂ or 9% CO ₂ dry
Particulate (mg/m ³)	10	30	20	5	35	30
HCl	10	50	100	10	40 or h = 95%	50
HF	1	2	1	1		2
SO ₂	50	300	200	40	85 or h = 85%	300
NO _x as NO ₂	70	350	180–300	70	350	200
CO	100			50	500	100
Total C	20			10		20
Dioxin, toxic equivalent (ng/m ³)	–		0.1	0.1		850°C, 2s ≥ 6% O ₂
Heavy metals (mg/ m ³)						
Total Class I	0.2					0.2
Cd	Cd + TI = 0.05	0.1	0.02	0.05		
Hg	0.05	0.1	0.03	0.05	0.14	
Total Class II	1.0					1.0
As						
Ni						
Total Class III	5.0		0.05 Pb + Zn			5.0 Pb, Cr Mn, Cu
Pb				5.0		
Cr						

6.2.6 Gas Cleaning System

Due to the stringent regulations imposed by the introduction of much national and worldwide legislation on MSWI emissions, the control of pollution emission has become a major part of the incineration process. A significant fraction of the total cost of an incinerator plant can be attributed to the provision for pollution control. Table 6.1 shows the emission limit for MSWIs in a number of countries in 1999 [28]. The main directives on emissions are the total particulate or dust in the gas,

concentration of acidic gases such as hydrogen fluoride and sulphur dioxide, hydrogen chloride, and heavy metals such as cadmium, mercury, lead, and dioxin. As can also be seen from Table 6.1, these limits are not the same for every country; for example, the emission limit for particulate in the United Kingdom is 30 mg/m^3 while the limit for the Netherlands is 5 mg/m^3 . It is the same with the emission limits of NO_x , where the emission limit in the United Kingdom is higher than in the Netherlands. The EC Directives also set a limit for the minimum combustion gas temperature of 850°C (1123 K), a residence time of 2 s , and a minimum oxygen level of 6% to ensure an efficient burn-out [28].

The increasingly stringent emission legislation has forced MSWI operators to install gas treatment plants downstream of their incinerators. The layout of a typical flue gas clean-up system for an MSWI is shown in Fig. 6.10. After the combustion gas from the incinerator exits the heat recovery boiler, the gas often enters a cyclone. This cyclone extracts particles larger than 15 m from the gas as a preliminary collector. The dusty gas stream reaches the cyclone from the side, forms a vortex, and rotates down the cyclone in a helical direction. By using centrifugal force, particles are isolated from the gas and fall to the bottom of the cyclone, where they are deposited. Smaller inlet-orifice cyclones increase collection performance for smaller particles, so they can be used in banks of small units [29].

The gas then flows from the cyclone into an electrostatic precipitator. For municipal waste incinerators, the electrostatic precipitator was once the most common form of particulate removal device. It can remove up to 99.5% of particulates in the flue gas, and it is particularly efficient in removing particles with submicron sizes [29].

The electrostatic precipitator contains an array of wires or thin metal rods with collector plates running between them. Fig. 6.11 shows how the particulates are removed from the flue gas in an electrostatic precipitator [29]. As the gas flows in between the collector plates, the particles are negatively charged by the electrodes. These negatively charged particles are then attached to the positively charged collector plates, where they accumulate and form a dust layer. A rotating hammer system is periodically used to clean the collector plates by “rapping” them to dislodge

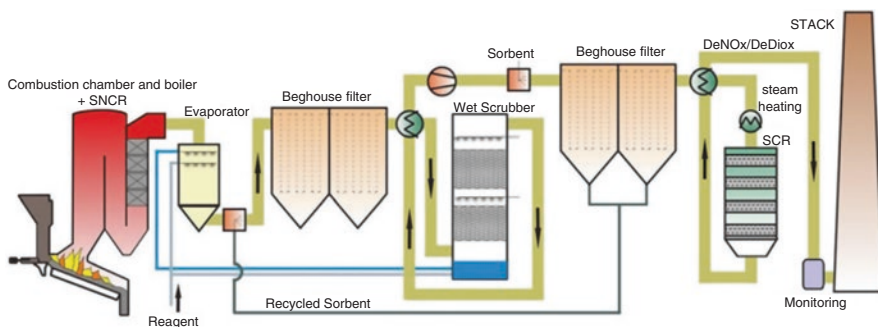


Fig. 6.10 Typical advanced gas clean-up for MSWI [21]

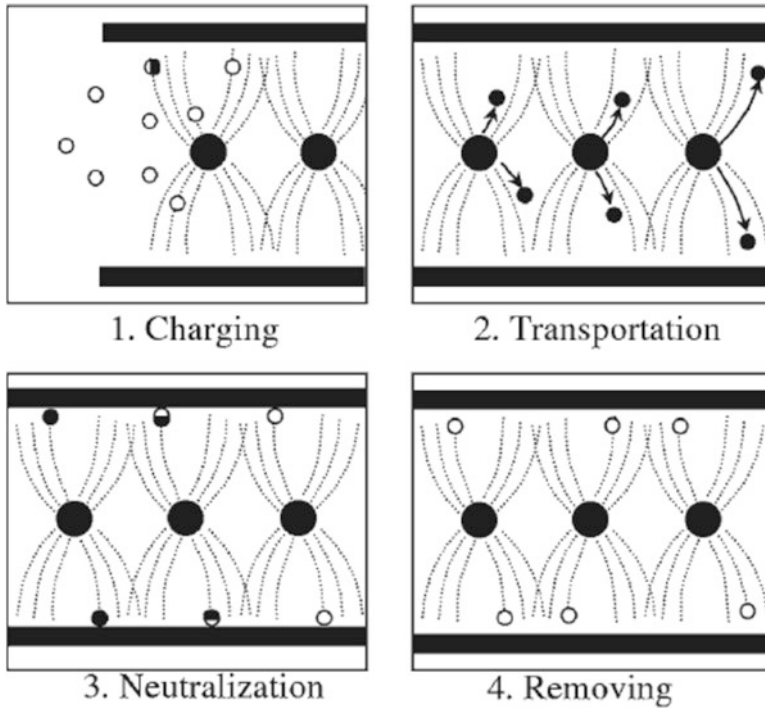


Fig. 6.11 Electrostatic precipitation principle [29]

the layers of accumulated particles. The dust then falls into the collector hopper at the bottom of the precipitator.

The gas then enters a wet, dry, or semi-dry scrubber for removal of soluble acids in it, such as hydrogen fluoride, hydrogen chloride, and sulphur dioxide. It also removes any remaining particulates and heavy metals in the flue gas. Fig. 6.12 shows an example of a wet scrubber.

In a wet scrubber, the gas is firstly cooled to about 60 °C (333 K) in a quench unit. It then enters the first stage of scrubbing, where it is sprayed with water to absorb the hydrogen chloride and hydrogen fluoride. This results in the formation of hydrochloric and hydrofluoric acid. The acid solution also removes the heavy metals in the gas as it flows through the unit. Using an alkaline solution such as lime (calcium hydroxide) or sodium hydroxide, the remaining hydrogen chloride and sulphur dioxide are extracted in the second step. After the de-mister stage, where any liquid carryover is eliminated, the gas exits the scrubber [28].

The dry scrubber system is commonly used in conjunction with fabric filters. As the cooled gas (160 °C) enters the tower, it is sprayed with a dry fine-grained powder, such as dry calcium hydroxide. The reactions between the calcium hydroxide, hydrogen chloride, and sulphur dioxide produce calcium chloride and calcium sulphate, respectively. The dry product is then allowed to drop to the bottom of the

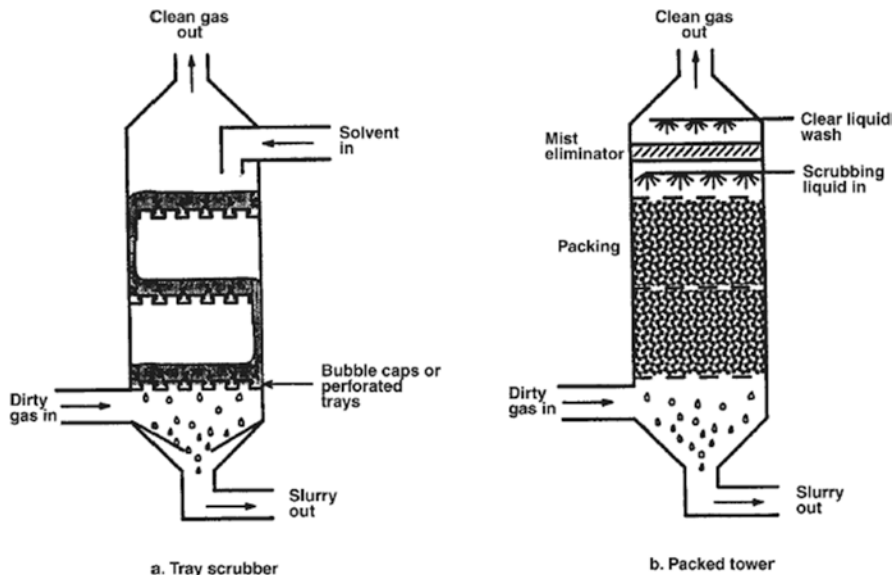


Fig. 6.12 Wet scrubber [29]

tower, where it is collected for further treatment or recycling. This system is also able to remove heavy metals and organic micropollutants by the addition of activated carbon to the calcium hydroxide [21, 23]. The semi-dry scrubber system is also commonly used in conjunction with fabric filters. Its function is the same as the dry scrubber except that droplets of calcium hydroxide solution are sprayed into the gas instead of the dry calcium hydroxide powder, and the water evaporates before the particles reach the wall or fabric filter.

The scrubbed gas then enters a fabric filter where any particulate matter, including fly ash and the activated carbon and lime containing the absorbed pollutant, is removed. After the electrostatic precipitator, scrubber, and injection of additives such as lime or activated carbon, fabric filters are used as the final clean-up stage. They are capable of removing particles as small as submicron from the gas stream, with a particle concentration of less than 10 mg/m^3 . A fabric filter is made up of a series of long, permeable fabric bags that are arranged within a baghouse or casing. Fig. 6.13 shows the particulate collection and cleaning processes that occur in a fabric filter. As the gas enters the filter bags, the fine fabric filters out the particulates from the gas stream. The accumulated particulate matter outside the filter bags is then removed by applying a pulse of air into the filter bags. This rapidly expands the bag and releases the accumulated particulates into the hopper located at the base of the baghouse [29].

Before the gas is discharged into the atmosphere, it is treated for the removal of NO_x . Nitrogen oxide (NO_x) emission can be reduced by controlling the combustion conditions and by treating the flue gas. The former method of controlling the NO_x formation is achieved by lowering the combustion temperature and the oxygen

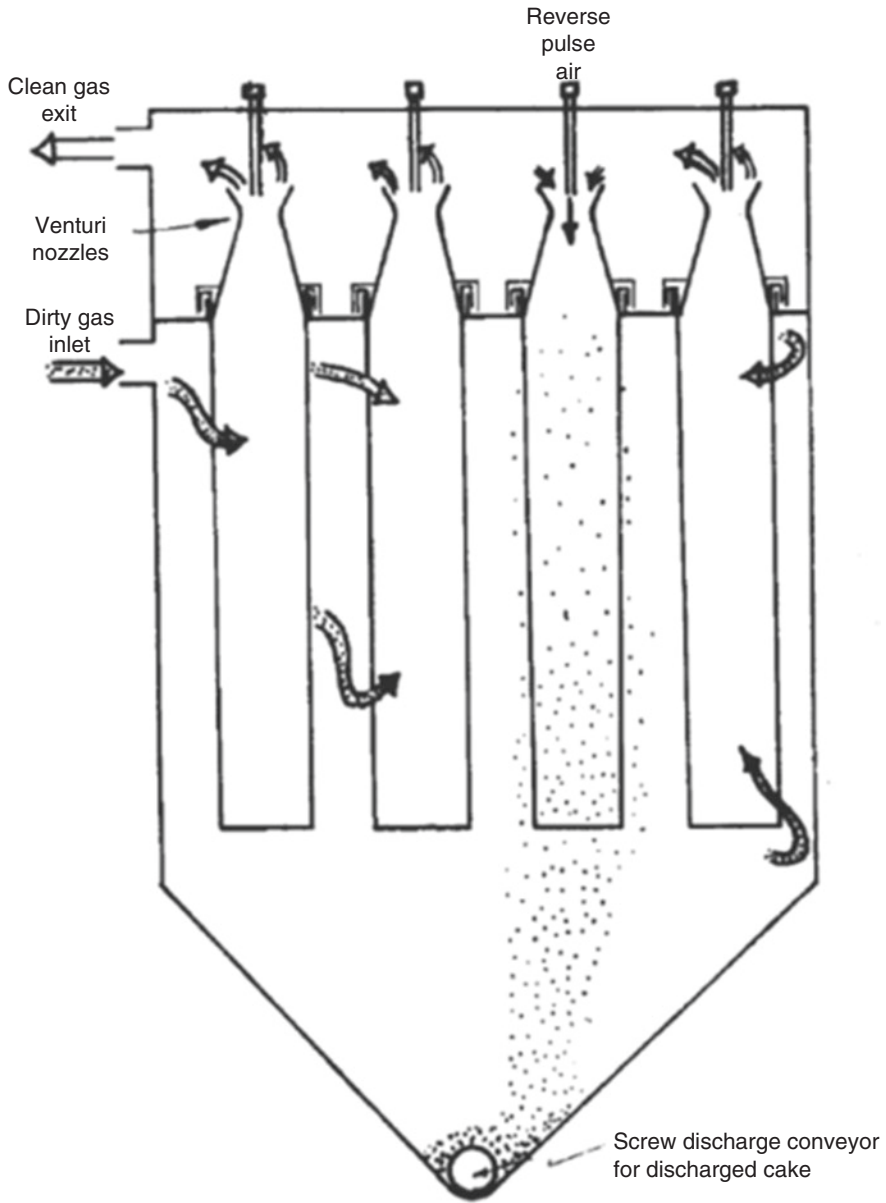


Fig. 6.13 Fabric filter [29]

levels. The latter removal method uses ammonia injection with or without the presence of a catalyst.

The process of ammonia injection where no catalyst is used is called the selective non-catalytic reduction (SNCR) process. This is achieved by injecting ammonia

into the gas at temperatures between 870 °C and 900 °C (597 K and 1173 K). This process reduces NO_x to nitrogen and water. SNCR reduces the NO_x level by 75–80% [29]. In the selective catalytic reduction (SCR) process, ammonia is injected into the gas stream in the presence of a catalyst at 300–400 °C (573–673 K) to produce nitrogen and water. Typical catalysts for the SCR process are palladium, platinum, titanium oxide, and vanadium oxide. This method reduces the NO_x level by over 90% [29].

6.2.7 Residue Processing and Disposal

Bottom ash and fly ash are the end products of the MSWI plant [23]. Bottom ash and fly ash have different properties depending on the type of incinerator and its location. It must be measured to ensure that the incinerator's combustion efficiency is maintained, as well as to ensure that hazardous substances like heavy metals, dioxins, and furans do not reach regulatory limits. Partially oxidised glass, metal, unburned organic material, inert mineral matter, and char are commonly found in bottom ash [22]. A magnetic separator can be used to recover oxidised metal. Others may be disposed of in landfills or processed for use as cement and building material raw materials [23]. After being treated with cement or a solvent, fly ash is normally disposed of in a managed disposal site [23].

Reburning or landfilling the oversize fraction, which contains the unburned combustible, is an option.

6.3 Other Types of Incinerators

6.3.1 Fluidised Bed-Type Incinerators

A fluidised bed incinerator has a layer of sand underneath the combustion chamber, which is blown into by air from the bottom to convert the sand into a fluid. The waste begins to burn on its own on the fluidised bed until the sand layer has been heated. Because of the sand's high heating power, even when waste with high moisture content is applied, it can dry and burn MSW instantly. Fluidised bed incinerators, on the other hand, can be restarted in a limited amount of time after they have stopped operating. However, if the incinerator is not properly built and controlled, incomplete combustion can result in high levels of CO gas due to the high combustion speed. This form of the incinerator is better suited to burning homogeneous materials like sludge than heterogeneous MSW.

6.3.2 *Gasification Melting Furnace*

The gasification melting furnace is a system that melts bottom ash directly in the furnace to create molten slag. Since molten slag has a higher density than bottom ash, it has greater potential as a construction material. In the gasification melting process, two types of furnaces are used: pyrolysis and gasification melting furnace with a fluidised bed or a kiln and a direct melting furnace with a vertical shaft furnace. Pyrolysis and gasification melting is a process in which waste is thermally decomposed with less oxygen or heated indirectly to induce pyrolysis (partial combustion) at a lower temperature than the combustion temperature, resulting in pyrolysis gas. In fluidised bed and kiln-type furnaces, this process occurs in each furnace that is separate from the melting furnace. In the second step, the pyrolysis gas is fully burned out at high temperatures, and solids are melted using the heat provided by combustion at temperatures of 1,200 to 1,300 °C. Kiln-type furnaces have become increasingly uncommon in recent years.

Waste moves down in a vertical middle pyrolysis layer and lower melting layer in a vertical shaft furnace melting phase. Because of its high costs and operational difficulties, the alternative of gasification melting has not been implemented as quickly as other methods in comparison to traditional incineration methods.

6.3.3 *Rotary Kilns*

Rotary kilns are exceptionally long-lasting and can burn almost any type of waste, regardless of their shape or composition. Rotary kilns are widely used for the incineration of hazardous wastes. This technology is commonly used to treat clinical waste, but it is not used to treat urban waste. Waste rotary kilns operate at temperatures ranging from 500 °C (as a gasifier) to 1450 °C. When traditional oxidative combustion is used, the temperature is usually above 850 °C. Temperatures of about 1200 °C are common when incinerating hazardous wastes. A schematic drawing of a rotary kiln incineration unit is shown in Fig. 6.14.

The rotary kiln is made up of a cylindrical vessel with a horizontal axis that is slightly inclined. The kiln is normally mounted on rollers, which allows it to rotate or oscillate around its axis (reciprocating motion). As the kiln rotates, gravity transports the waste into it. Rotary kilns can burn solid waste, liquid waste, gaseous waste, and sludges. A post-combustion chamber is normally inserted to maximise the degradation of toxic compounds. The additional firing of liquid waste or additional fuel may be necessary to sustain the temperatures needed for the waste to be incinerated and be destroyed.

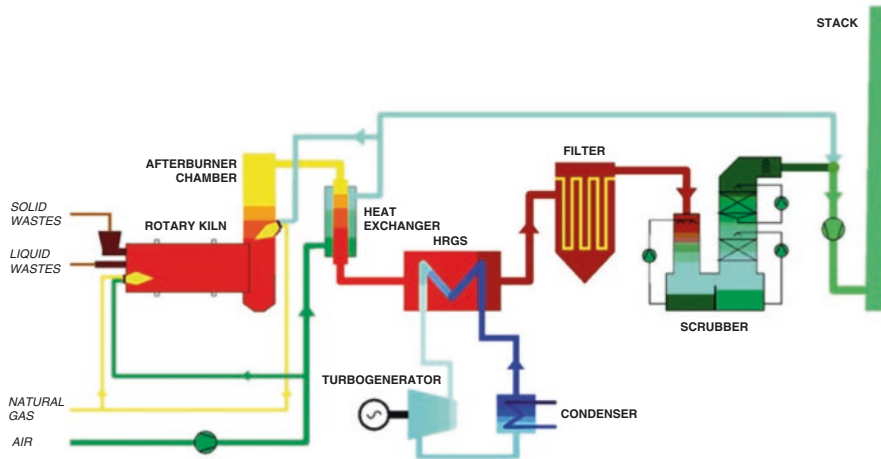


Fig. 6.14 Schematic of a rotary kiln incinerator plant [21]

6.3.4 Plasma Technologies

Electrons, ions, and neutral particles make up plasma (atoms and molecules). The interaction of gas with an electric or magnetic field will produce this high-temperature, ionised, conductive gas. Plasmas contain reactive species, and the high temperatures encourage chemical reactions to occur quickly. To create a plasma, plasma processes use high temperatures (5000 to 15000 °C) that result from the conversion of electrical energy to heat. They entail moving a huge electric current through a gas stream that is inert. Hazardous pollutants such as PCBs, dioxins, furans, toxins, and others are broken down into their atomic constituents by injecting them into the plasma under these conditions. Organics, metals, PCBs (including small-scale equipment), and HCB are all treated using this method. In many cases, waste pre-treatment is needed. The technology's destruction efficiencies are very high, at >99.99%. Plasma technology is a well-established commercial technology, but it can be a difficult, costly, and labour-intensive operation. The following are some examples of plasma technologies.

6.3.4.1 Argon Plasma Arc

The waste reacts with the argon plasma jet directly. Since it is inert and does not react with the torch elements, argon was chosen as the plasma gas. The destruction and removal efficiency (DRE) for destroying ozone-depleting substances (ODS) at 120 kg/h and 150 kW electrical power is stated to be greater than 99.9998%.

6.3.4.2 Inductively Coupled Radio Frequency (ICRF) Plasma

Inductively coupled plasma torches are used in ICRF applications, and energy is transferred to the plasma through the electromagnetic field of the induction coil. Since there are no electrodes, the device can be used for a wide variety of gases, including inert, reducing, or oxidising atmospheres, and it is more reliable than plasma arc methods. The ICRF plasma process has a DRE of over 99.99% and can kill CFC at a rate of 50 to 80 kg/h.

6.3.4.3 Alternating Current (AC) Plasma

The AC plasma is similar to the ICRF plasma in that it is generated directly with 60 Hz high voltage power. The device is believed to be very reliable because it is electrically and mechanically simple. The method does not need argon and can operate with a number of working gases, such as air or steam as plasma gases.

6.3.4.4 CO₂ Plasma Arc

Sending a strong electric discharge into an inert atmospheric gas, such as argon, produces a high-temperature plasma. Depending on the desired process outcomes, the plasma field is maintained with ordinary compressed air or certain atmospheric gases once it has been created. The temperature of the plasma at the point of generation, into which the liquid or gaseous waste is directly pumped, is well over 5000 °C. The temperature in the upper reactor is about 3500 °F, and it gradually drops across the reaction zone to a precisely regulated temperature of around 1300 °F. The use of CO₂, which is produced during the oxidation reaction, as the gas to support the plasma is a unique feature of the process.

6.3.4.5 Microwave Plasma

This method uses microwave energy at 2.45 GHz to produce thermal plasma under atmospheric pressure in a specially built coaxial cavity. The plasma is started with argon, but the process does not need any gas to keep the plasma going. The microwave plasma process is said to have a DRE of over 99.99%, killing CFC-12 at a rate of 2 kg/h. The process's high destruction efficiency is a key benefit. The process is said to be capable of reaching high operating temperatures in a limited amount of time, allowing for greater operational flexibility and less downtime.

6.3.4.6 Nitrogen Plasma Arc

This method produces thermal plasma using a direct current (DC) non-transferred plasma torch with water-cooled electrodes and nitrogen as the working gas. The process was created in 1995, and commercial systems are now available. At a feed rate of 10 kg/h, the process is said to achieve a DRE of 99.99% when destroying CFCs, HCFCs, and HFCs. The equipment is very small, which is a major benefit of this technology.

6.4 Incineration Process

Incineration is a complex process involving the disciplines of chemical and mechanical engineering. To fully understand this process, one must understand the fundamental of incineration, which is its stoichiometry. This involves studying its fundamental relations, material balances, energy balance, equilibrium, and kinetics. In addition, a wide range of waste compositions must also be taken into consideration. In most cases, waste incinerator operators have limited or no control of the precise composition of the incoming waste. However, mass-burn incinerators must be designed to cope with the wide range of waste compositions. Owing to the difficulties ensuring acceptable composition for the incineration process, a triangle diagram was developed, as shown in Fig. 6.15 [30]. The diagram was created to

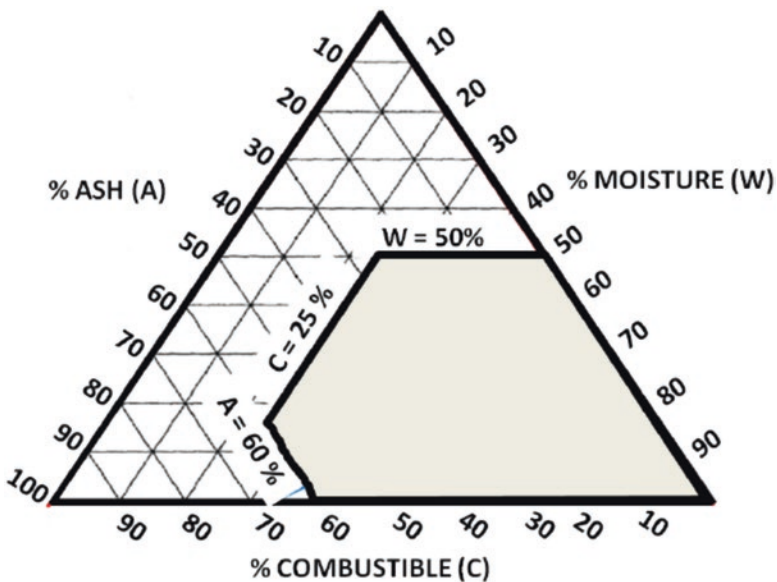


Fig. 6.15 Suitability of MSW composition for incineration [30]

confirm whether the current proximate composition (moisture, ash, and volatile) of municipal solid waste will be appropriate for incineration based on the close relationship between waste composition and calorific value CV. The shaded area depicts a typical municipal solid waste composition that can withstand combustion without the use of auxiliary fuel. The region encompasses the minimum allowable CV as well as the maximum moisture content that can be tolerated. The following parts will go into how to calculate and test the above parameters.

Incineration technology, for example, can be used on waste with a moisture content of 75% or less and volatile content of 20% or more, resulting in a CV of 3,352 kJ/kg or more. Furthermore, these technologies are typically applicable for waste with a moisture content of 65% or less and volatile content of 30% or more, with a CV of 6,285 kJ/kg or more, in cases where energy recovery is a part of the incineration process.

When looking at the overall composition of waste, the proportion of food and kitchen waste with high moisture levels has the greatest effect. Incineration becomes a viable choice when the volume of organic waste is between 50% and 60%. It is not, however, ideal for energy recovery, which is only possible when the proportion of plastic to paper increases and the proportion of food and kitchen waste falls to about 50% or less.

6.4.1 Fundamental Relationships

In dealing with the incineration process, one must be familiar with a few chemical and mechanical knowledge related to gas laws, material balances, heat balances, equilibrium, and kinetics. The following subsection will discuss them further.

6.4.1.1 Gas Laws

The ideal gas law is described by Eq. 6.1,

$$PV = nRT \quad (6.1)$$

where P is the absolute pressure, T is the absolute temperature, V is its volume, n is the number of moles of the gas, and R is the universal gas for ideal gases. Table 6.2

Table 6.2 Values of the gas constant R for ideal gases [22]

Pressure	Volume	Moles	Temperature	R
atm	m ³	kg-mol	K	0.08206 m ³ -atm kg-mol ⁻¹ K ⁻¹
psia	ft ³	lb-mol	°R	1543 ft-lb lb-mol ⁻¹ °R ⁻¹
atm	ft ³	lb-mol	°R	0.729 ft ³ -atm lb-mol ⁻¹ °R ⁻¹
–	–	kg-mol	K	1.986 kcal kg-mol ⁻¹ K ⁻¹

shows values of the gas constant r for an ideal gas [22]. Example 1 will give an overview of how much CO_2 will be produced from an incineration process.

Example 1. An incineration plant is needed to process 6000 kg of waste per day with an average carbon content of 80%, ash content of 7%, and moisture content of 13%. The combustion gases leave the furnace at 1100 °F and pass through a gas cooler before exiting at 90 °F. On a daily basis, how many kilogram-moles and kilograms of CO_2 will be produced? At 1.04 atm, how many cubic meters of CO_2 are emitted per day at the furnace and gas cooler outlets?

The waste contains $(6000)(0.80)(1/12) = 400$ moles of carbon (atomic weight = 12). In full combustion, each mole of carbon emits 1 mole of CO_2 , resulting in 400 mol/d of CO_2 . CO_2 (molecular weight 44) has a weight flow of $400(44) = 17600$ kg/d.

$$\text{From } PV = nRT$$

$$V = \frac{nRT}{P} = \frac{400(0.08206)T}{1.04} = 15.78T$$

At 1100 °C (1373 K), $V = 43,334 \text{ m}^3$. At 90 °C (363 K), $V = 11,457 \text{ m}^3$.

6.4.1.2 Material Balances

Calculation of material balances is very important in order to know the amount of theoretical air required to completely oxidise carbon, hydrogen, sulphur, etc. It can be represented by the following equation:

$$\text{Input} = \text{output} + \text{accumulation} \quad (6.2)$$

This equation represented a quantitative expression of the law of conservation of matter and is always true for all the elements that pass through a combustion system. However, it is not true for an individual compound that took part in the combustion reaction. The basic data for material balance calculation are the analyses of fuel or waste, gases in the system, reaction rate, proportions in molecules, and heat of reactions. Through this balance on elements in the fuel or waste, the amount of theoretical air required to completely oxidise carbon, hydrogen, sulphur, etc. can be calculated. This theoretical or stoichiometric air requirement is often insufficient in a practical combustor; thus, an excess air must always be supplied. For example, an incinerator operating at 50% excess air denotes a combustion process to which 1.5 times the stoichiometric air requirement has been supplied.

The following is an example of theoretical air calculation for a combustion process.

Example 2. The ultimate analysis of 100 kg/h of waste at an incinerator shows that it has 12.2% moisture, 75% carbon, 5.2% hydrogen, 2.4% sulphur, 2.1% oxygen, 0.5% nitrogen, and 1.6% ash. The combustion air is at 15.5 °C and has 70% relative humidity. Calculate the amount of air needed and products of combustion when it operates at 50% excess air. The sequence of computations is shown in Table 6.3.

Shown below are several elements of the analysis [7]:

- (a) Line 1: Carbon is assumed to be entirely converted to carbon dioxide during combustion.
- (b) Line 2: The volume of combustion air is increased by hydrogen in the waste (other than hydrogen in moisture), but this is not accounted for in the Orsat study (Lines 16 and 17).
- (c) Line 3: Sulphur in the waste, in the form of sulphide or organic sulphur, increases the amount of combustion air needed for SO₂ combustion. Sulphates inorganic can be left as ash or reduced to SO₂. SO₂ (Line 17) is normally listed out as carbon dioxide if the selective analysis is not used.
- (d) Line 4: The amount of necessary combustion air is reduced due to the presence of oxygen in the waste.
- (e) Line 12: Moisture entering the combustion air appears to be minor and is often overlooked. Despite the fact that this issue only considered waste components of C, H, O, N, and S, the analyst should thoroughly analyse the waste composition and consider the following secondary reactions:
- (f) Carbon monoxide is a poisonous gas. CO is generated in significant amounts in solids-burning systems.
- (g) Chlorine is a chemical that is used to kill bacteria. Chlorine that appears in waste as inorganic salts will almost certainly remain as salt. Organic chlorides, on the other hand, mainly produce hydrogen chloride.
- (h) Metals are a type of metal. While a significant fraction of massive metal feed (e.g., tin cans, sheet steel, etc.) is unoxidised in solid waste burning, metals typically burn to the oxide.
- (i) Decomposition due to heat. Some compounds can decompose at high temperatures in the combustor. Carbonates, for example, can dissociate to produce oxide and CO₂, while sulphides can “roast” to produce oxide and SO₂.

Another method of calculation can be done by evaluating an existing MSWI. Here, flue gas composition data can easily be obtained; thus, the operation and the feed waste can be characterised at a much cheaper cost. The percentage of excess air can be calculated using the flue gas composition obtained and the following equation:

$$\text{Percentage excess air} = \frac{[O_2 - 0.5(CO + H_2)]100}{0.266N_2 - O_2 + 0.5(CO + H_2)} \quad (6.3)$$

where O₂, N₂ etc., are the volume percentages of the gases on a dry basis. Example 3 will show how Eq. 6.3 is used.

Table 6.3 Calculations for Example 2

Line	Component	Atoms or moles		Combustion product	Theoretical moles of O ₂ required	Moles formed in stoichiometric combustion						
		kg	^a			CO ₂	H ₂ O	SO ₂	N ₂	O ₂	Total	
1	Carbon, C	75.0	6.250	CO ₂	6.250	6.250	0.0	0.0	0.0	0.0	0.0	6.250
2	Hydrogen, H ₂	6.2	3.100	H ₂ O	1.550	0.0	3.1	0.0	0.0	0.0	0.0	3.100
3	Sulfur, S	2.4	0.075	SO ₂	0.075	0.0	0.0	0.075	0.0	0.0	0.0	0.075
4	Oxygen, O ₂	2.1	0.066	-	(0.066)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	Nitrogen, N ₂	0.5	0.018	N ₂	0.0	0.0	0.0	0.0	0.018	0.0	0.0	0.018
6	Moisture, H ₂ O	12.2	0.678	H ₂ O	0.0	0.0	0.678	0.0	0.0	0.0	0.0	0.678
7	Ash	1.6	N/A	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	Total	100.0			7.809	6.250	3.778	0.075	0.018	0.0	0.0	10.121
9	Moles of nitrogen in stoichiometric air ^b			(79/21) (7.809)					29.377			29.377
10	Moles of nitrogen in excess air			(0.5)(79/21)(7.809)					14.688			14.688
11	Moles of oxygen in excess air			(0.5) (7.809)								3.905
12	Moles moisture in combustion air ^c						0.604					0.604
13	Total moles in flue gas					6.250	4.382	0.075	44.083	3.905		58.695
14	Volume (mole) percentage in wet flue gas					10.648	7.466	0.128	75.105	6.653		100.0
15	Orsat (dry) flue gas analysis, moles					6.250		0.075	44.083	3.905		54.313
16	A. With selective SO ₂ testing, volume percentage					11.508	N/A	0.138	81.164	7.180		100.0
17	B. With alkaline CO ₂ testing only, volume percentage					11.646	N/A	N/A	81.164	7.190		100.0

^aThe symbol in the component column shows whether these are kg-mol or kg-atom

^bThroughout this chapter, dry combustion air is assumed to contain 21.0% oxygen by volume and 79.0% nitrogen

^cCalculated as follows: (0.008/18)[(29.377 + 14.688)(28) + (3.905)(32)] based on the assumption of 0.008 kg water vapor per kg bone-dry air; found from standard psychrometric charts

Example 3. An incinerator that burns a specific amount of waste emits flue gas that contains 11.6% CO₂, 7.2% O₂, and the remaining nitrogen and inerts. Calculate the weight ratio of hydrogen to carbon in the waste, the percentage of carbon and hydrogen in the dry waste, the kilograms of dry air used per pound of dry waste, the percentage of excess air used, and the moles of exhaust gas discharged per kilogram of dry waste burned using these statistics. (It should be noted that this example is based on Example 2.)

As a starting point: 100 mol dry exhaust gas

Component	Moles	Mol O ₂
CO ₂ + (SO ₂)	11.6	11.6
O ₂	7.2	7.2
N ₂	81.2	–
Total	100.0	18.8

If all N₂ comes from the combustion air, a total of $81.2 \times (21/79) = 21.6$ mol O₂ is entered with the N₂. The difference, $21.6 - 18.8 = 2.8$ mol O₂, can be assumed to have been consumed in burning hydrogen.

H ₂ burned: $2(2.8) = 5.6$ mol	11.6 kg
C burned : $12(11.6) = 139.2$ mol	139.2 kg
	150.4 kg

- (a) Weight ratio of hydrogen to carbon: $(11.2/139.2) = 0.08$.
 (b) Percentage (by weight) of C in dry fuel: $(139.2/150.4)(100) = 92.55$.
 (c) Kilogram of dry air per kilogram of dry waste.

First, calculate the weight of air resulting in 1 mol dry exhaust gas from a nitrogen balance:

$$1/100 \times (81.2 \text{ mol N}_2) / (1/0.79 \text{ mol N}_2/\text{mol air})(29 \text{ kg air/mol}) = 29.81 \text{ kg air/mol dry exhaust gas.}$$

Then, $29.81(100/150)$ mol dry exhaust gas/kg waste = 19.87 kg dry air/kg dry waste.

- (d) Percentage of excess air:

The oxygen necessary for combustion is $11.6 + 2.8 = 14.4$ mol

The oxygen unnecessary for combustion = 7.2 mol

The total oxygen = 21.6 mol.

The percentage of excess air (or oxygen) may be calculated as

$$\frac{(100)(\text{unnecessary})}{\text{total} - \text{unnecessary}} = \frac{100(7.2)}{21.6 - 7.2} = 50\%$$

$$\frac{(100)\text{unnecessary}}{\text{necessary}} = \frac{100(7.2)}{14.4} = 50\%$$

$$\frac{(100)(\text{total} - \text{necessary})}{\text{necessary}} = \frac{100(21.6 - 14.4)}{14.4} = 50\%$$

(e) Moles of exhaust gas per kilogram of dry waste:

Noting that 5.6 mol water vapour must be added to the dry gas flow, $(100 + 5.6)/150 = 0.702$ mol/kg fuel.

It is necessary to realise that in calculating the excess air, an engineer needs to acknowledge that [7]

- The results of the waste analysis are crucial in determining the amount of combustion air needed for construction.
- Waste moisture data are needed to calculate total flue gas rates.
- Stack gas analysis may provide information about the waste's composition.
- If data are available, cross-check all data for both fuel and flue gas to ensure accuracy.

6.4.1.3 Heat Balances

A heat balance is a numerical expression of the law of energy conservation. Five energy amounts are of primary importance in waste incineration:

- **Chemical Energy.** It is a term that refers to the energy that heat produced by chemical reactions, especially combustion.
- **Latent Heat.** The heat effect of state changes, especially the heat of moisture vaporisation.
- **Sensible Heat.** The heat content (enthalpy) of materials is proportional to their temperature.
- **Useful Heat.** The heat that can be used, especially the sensible heat that can be used to generate steam.
- **Heat Loss.** Through conduction, convection, and radiation, heat is lost through the furnace walls.

The value of heat of combustion and sensible heat are readily available in the literature, usually known as higher heating value (HHV). One can just use it for further calculation. The sensible heat content (Δh) at a temperature T may be calculated relative to the reference temperature T_0 by

$$\Delta h = \int_{T_0}^T MC_p^0 dT \text{ kcal / kg mol} \quad (6.4)$$

where MC_p^0 is the molar heat capacity ($\text{kcal mol}^{-1} \text{ }^\circ\text{C}^{-1}$). Another way to calculate Δh is by using $MC_{p\text{avg}}^0$ from Fig. 6.16 and using the following equation:

$$\Delta h = (T - T_0)(MC_{p\text{avg}}^0) \quad (6.5)$$

Example 4. If the 100 kg of waste in Example 2 has a heat of combustion of 7500 kcal/kg (HHV) and the combustion air is pre-heated to 300 °C, what is the tempera-

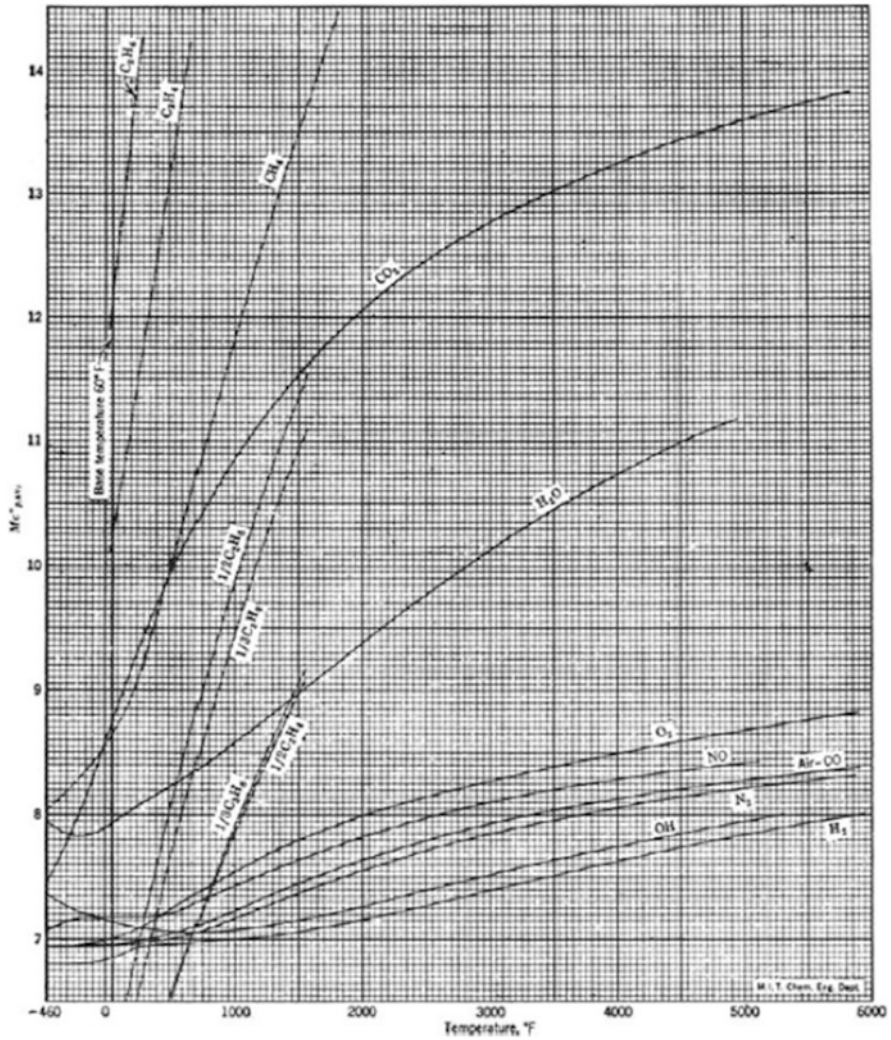


Fig. 6.16 Average molar heat capacity of fuel and combustion gases, using $M C_{p,avg}^0$ at zero pressure between 60°F (15.6 °C) and abscissa temperature [7]

ture of the flue gases? When gases are cooled to 180°C (about 350°F) in a boiler, how much steam can be produced? At 204°C, assume a 5% heat loss in the furnace and a 5% heat loss in the boiler, as well as a 570 kcal/kg enthalpy transition from boiler feedwater to produce steam and 1 h service as a base.

The total combustion air supplied to the system is $29.377 + 14.688 + 3(3.905) + 0.604 = 56.384$ mol (see Table 6.3). From Fig. 6.20, the heat content of the pre-heated air at 300 °C is

$$(56.384)(7.08)(300 - 15.5) = 113,572 \text{ kcal}$$

therefore, the total energy impact is

$$7500(100) + 113,572 = 863,572 \text{ kcal energy addition}$$

To determine the combustion chamber's exit temperature and steaming rate, create a plot of the heat content of the gas stream as a function of temperature, as shown in Table 6.4 and shown in Fig. 6.17. Table 6.5 depicts the flow of thermal energy. The enthalpy transition for feedwater (at 100 °C and 15.8 atm) transitioning to saturated steam at 15.8 atm is 567.9 kcal/kg, resulting in the following steaming rate for a burning rate of 1100 kg/h: $661,757/567.9 = 1165 \text{ kg/h}$

For feedwater (at 100 °C and 15.8 atm) changing to saturated steam at 15.8 atm, the enthalpy change is 567.9 kcal/kg, so the resulting steaming rate for a burning rate of 1100 kg/h is

$$(661,757/567.9) \text{ g} = 1165 \text{ kg/h}$$

Table 6.4 Computation of heat content of flue gases from combustion of benzene waste at 10% excess air

A. Assumed temp., °C	180	500	1,000	1,500	2,000
B. A - 15.5 °C	164.5	484.5	984.5	1,484.5	1,984.5
C. $Mc^{\circ}p_{\text{avg}}N_2^a$	7.00	7.13	7.48	7.76	8.00
D. $Mc^{\circ}p_{\text{avg}}O_2$	7.10	7.50	7.92	8.20	8.40
E. $Mc^{\circ}p_{\text{avg}}H_2O$	8.10	8.52	9.23	9.90	10.50
F. $Mc^{\circ}p_{\text{avg}}CO_2$	9.42	10.75	11.90	12.60	13.08
G. Ash ^b	0.2	0.2	0.2	0.2	0.2
H. 44.083(B)(C)	50,750	152,250	324,480	507,925	699,850
I. 3.905 (B)(D)	4,740	14,230	30,565	47,430	65,350
J. 4.382 (B)(E)	5,825	18,125	39,870	64,340	91,265
K. 6.25 (B)(F)	9,680	32,540	73,210	116,910	162,210
L. 1.6(B)(G) + 85 ^c	190	290	450	610	770
M. 4.382 (10,595) ^d	46,430	46,430	46,430	46,430	46,430
N. (H + I + J + K + L + M) ^e	117,615	263,865	515,005	783,645	1,065,875
O. kcal/mol gas	2,004	4,495	8,774	13,351	18,160

^aSource: Fig. 6.16 (kcal/kg mol °C)

^bSpecific heat of the ash (kcal/kg °C) for solid or liquid

^cThe latent heat of fusion of the ash (85 kcal/kg) is added at temperatures greater than 800 °C, the assumed ash fusion temperature

^dLatent heat of vaporization at 15.5 °C of free water in waste and from combustion of hydrogen in waste (kcal/kg mol)

^eTotal heat content of gas stream (kcal)

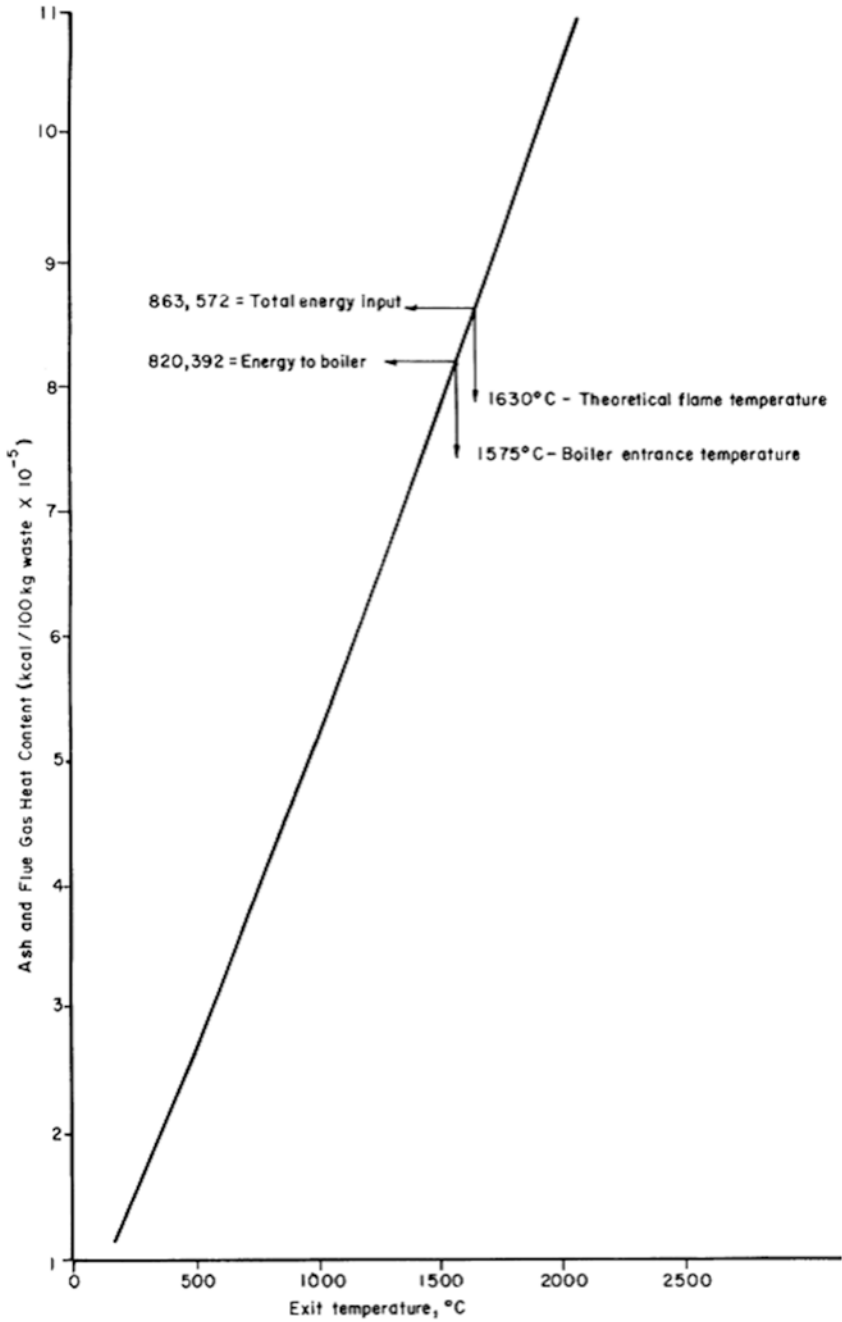


Fig. 6.17 The heat content of exhaust gases relative to 15.5 °C [7]

Table 6.5 Energy flow calculation for Example 4 [7]

Energy flows	kcal	Temperature, °C
Energy into system		
Heat of combustion	750,000	15.5
Air preheat	113,572	300
Total	863,572	1,630°
Heat loss (5%) from combustion chamber	(43,180)	
Energy into boiler	820,392	1,575
Heat loss (5%) from boiler	(41,020)	
Heat loss out stack	(117,615)	180
Net energy into steam	661,757	204

The theoretical (adiabatic) flame temperature for this system (the temperature of the products of combustion assuming no heat loss)

6.4.1.4 Equilibrium

The complete chemical reaction does not exist because some fraction of the reactants remain in the reaction mass. For the gas-phase reaction,



where the reactant and product concentrations are expressed as partial pressures and the equilibrium constant K_p , which is a function (only) of temperature, is given by

$$K_p = \frac{P_C^c P_D^d}{P_A^a P_B^b} \quad (6.7)$$

where the units of K_p depend on the stoichiometric coefficients a , b , c , and d such that if $(c + d - a - b)$ is zero, K_p is dimensionless. If the total is nonzero, K_p will have the units of pressure raised to the appropriate integer or fractional power.

Fig. 6.18 shows the temperature dependence of reactions of interest. Note that when solid carbon is a product or reactant, no partial pressure term for carbon is entered into the mathematical formulation.

Example 5. At the furnace outlet temperature in Example 4 and at a total pressure of 1 atm, what is the emission rate of nitric oxide (NO) formed by the reaction?



From Fig. 6.18 at 1575 °C, $\log K_p = 1.9$ ($K_p = 79.43$) where

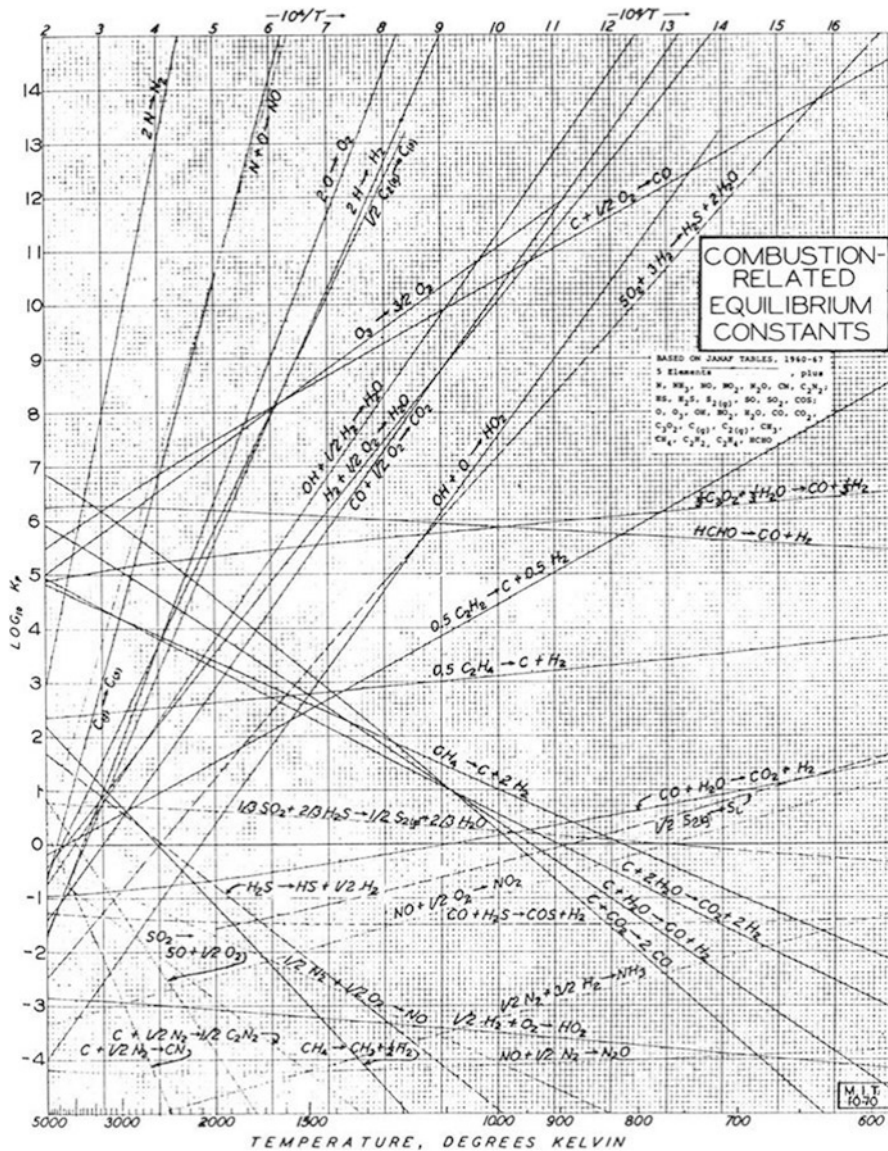


Fig. 6.18 Equilibrium constants of combustion reactions (partial pressure in atm) [7]

$$K_p = P_{O_2}^{1/2} P_{N_2}^{1/2} / P_{NO} \tag{6.9}$$

At equilibrium, then

$$(3.905 - 0.5X)^{1/2} (44.083 - 0.5X)^{1/2} = 79.43x$$

Solving for x resulted in $x = 0.164$ mol NO at equilibrium, or 0.279 mol/o or 2794 ppm. Note, however, that kinetic limitations usually result in NO concentrations substantially below those predicted by equilibrium alone [7].

6.4.1.5 Kinetics

Temperature, as well as the concentrations of the reactants and the static pressure (for gas-phase reactions), are all essential factors in chemical reactions. At combustion temperatures, reactions are normally very rapid. The oxidation reactions for carbon monoxide (CO), soot (carbon), and chlorinated hydrocarbons are notable exceptions. The previous publication addressed the reaction rate activity (chemical kinetics) of CO and soot burning [7]. Temperature, as well as the concentrations of the reactants and the static pressure (for gas-phase reactions), are all essential factors in chemical reactions. At combustion temperatures, reactions are normally very rapid. The oxidation reactions for carbon monoxide (CO), soot (carbon), and chlorinated hydrocarbons are notable exceptions. The previous publication addressed the reaction rate activity (chemical kinetics) of CO and soot burning [7].

Kinetics of Carbon Monoxide Oxidation

Carbon monoxide (CO) is an essential air pollutant, a hazardous gas in high concentrations, and represents unavailable combustion energy if present in stack gases. The rate expression for the rate of change of the CO mol fraction (f_{CO}) with time can be expressed by [7]

$$\frac{-df_{CO}}{dt} = 12 \times 10^{10} \exp\left[-\frac{16,000}{RT}\right] f_{O_2}^{0.3} f_{CO} f_{H_2O}^{0.5} \left[\frac{P}{R'T}\right] \quad (6.10)$$

where f_{CO} , f_{O_2} , and f_{H_2O} are the mole fractions of CO, O₂, and water vapor, respectively, T is the absolute temperature (K), P is the absolute pressure (atm), t is the time in seconds, and R and R' are the gas constant expressed as 1.986 cal g mol⁻¹ K⁻¹ and 82.06 atm cm³ g mol⁻¹ K⁻¹, respectively.

The term $(-16,000/RT)$ is the kinetic expression's core, providing a high-temperature sensitivity by exponentiating the ratio of 16,000 (the Arrhenius "activation energy") to the absolute temperature.

The rate of reaction is affected by the amount of water vapour present, which reflects the position of hydrogen (H) and hydroxyl (OH) free radicals in combustion reactions. In reality, bone-dry CO is extremely difficult to burn, while even a smid-geon of moisture is enough to aid ignition and rapid combustion.

Kinetics of Soot Oxidation

Soot (finely divided carbon) formation is another drawback of burning carbon-bearing wastes. This is the black smoke we see when combustion occurs at a very low oxygen level. It can cause device problems by fouling boiler tube surfaces, reducing the collection efficiency of electrostatic precipitators, and so on, resulting in violations of opacity regulations that apply to stack discharges. In contrast to many other combustion reactions, soot burn-out is relatively slow. The rate of carbon consumption q ($\text{g cm}^{-2} \text{S}^{-1}$) to the oxygen partial pressure in atmospheres (P_{O_2}) is given by the following equation for spherical particles:

$$q = \frac{P_{O_2}}{1/k_s + 1/k_d} \quad (6.11)$$

where k_s is the kinetic rate constant for the consumption reaction and k_d is the diffusional rate constant. For particles of diameter d (cm) at a temperature T (K),

$$k_d = \frac{4.335 \times 10^{-6} T^{0.65}}{d} \quad (6.12)$$

$$k_s = 0.13 \exp \left[(-35,700/R) \left(\frac{1}{T} - \frac{1}{1600} \right) \right] \quad (6.13)$$

where R is the gas constant ($1.986 \text{ cal g-mol}^{-1} \text{ K}^{-1}$). For a particle of initial diameter d_o and an assumed specific gravity of 2, the time t_b in seconds to completely burn out the soot particle is given by

$$t_b = \frac{1}{P_{O_2}} \left[\frac{d_o}{0.13 \exp \left[\left(\frac{-35,700}{R} \right) \left(\frac{1}{T} - \frac{1}{1600} \right) \right]} + \frac{d_o^2}{8.67 \times 10^{-6} T^{1.75}} \right] \quad (6.14)$$

6.4.2 Thermal Decomposition (Pyrolysis)

Pyrolysis is a burning process in the absence of a limited air supply. It generates a low-heat-content stream containing volatilised water, a mixture of CO, hydrogen, and hydrocarbons, and a solid char that is often fully burned in a specialised region of the “pyrolyser.”

Pyrolysis starts around 200 °C. It generates complicated partially oxidised tars. If the temperature rises, these materials degrade further, giving way to simpler, more hydrogen-rich gaseous compounds and solid carbon. In terms of chemical composition and physical structure, the solid residue is similar to graphitic carbon.

In pyrolysis, the rate-controlling stage may be either the heat transfer rate into the solid or the chemical reaction rate. For waste pieces less than 1 cm in size, the pyrolysis reactions appear rate-controlling below 500 °C. Pyrolysis reactions are quick over 500 °C, and both heat transfer and product diffusion are rate-limiting. Heat transfer is likely to dominate for all temperatures of practical interest for parts larger than 5 cm.

6.4.2.1 Pyrolysis Time

The rate of heating controlled the time required for the pyrolysis of most wastes. Figs. 6.19 and 6.20 show how long it takes for the centre temperature of plates and spheres to increase by 95% of the initial temperature difference between the specimen and its surroundings. Thermal diffusivity of 3.6×10^{-4} m²/h has been assumed, which is approximately equivalent to the thermal diffusivity of paper or wood [7]. At infinite cross-flow velocity (V), the heating time corresponds to radiant heating.

6.4.2.2 Pyrolysis Product

In the solid phase, pyrolysis reactions produce ash and carbonaceous char; in the liquid phase, water, various alcohols, ketones, acetic acid, methanol, 2-methyl-1-propanol, 1-pentanol, 3-pentanol, 1,3-propanediol, and 1-hexanol; and in the gas phase, carbon dioxide, carbon monoxide, hydrogen, and a number of low moles [7]. The distribution of these items is affected by the heating rate, ultimate temperature, and moisture content. Table 6.6 displays the yield of pyrolysis products from various substrates. Tables 6.7, 6.8, 6.9 and 6.10 display the impact of final temperature and heating rate on product mix. Table 6.11 depicts the major variations in gas composition and heat content for various feed materials, while Table 6.12 depicts the distribution of the elements comprising mixed municipal refuse.

6.4.2.3 Decomposition Kinetics

Cellulose pyrolysis appears to be a two-step procedure. The step entails breaking the C–O–C bond to produce a mixture of sugar-like molecules, which are then degraded by breaking the C–O–C bond again. The pyrolysis reaction can be computed using

$$\frac{dp}{dt} = -10^6 (\rho - \rho_c) \exp\left(\frac{-19,000}{R_T}\right) \quad (6.15)$$

where ρ is the instantaneous density (g/cm³) and the subscript c denotes char, t is time (min), R is the gas constant (1.987 cal/mol K), and T is the absolute temperature (K).

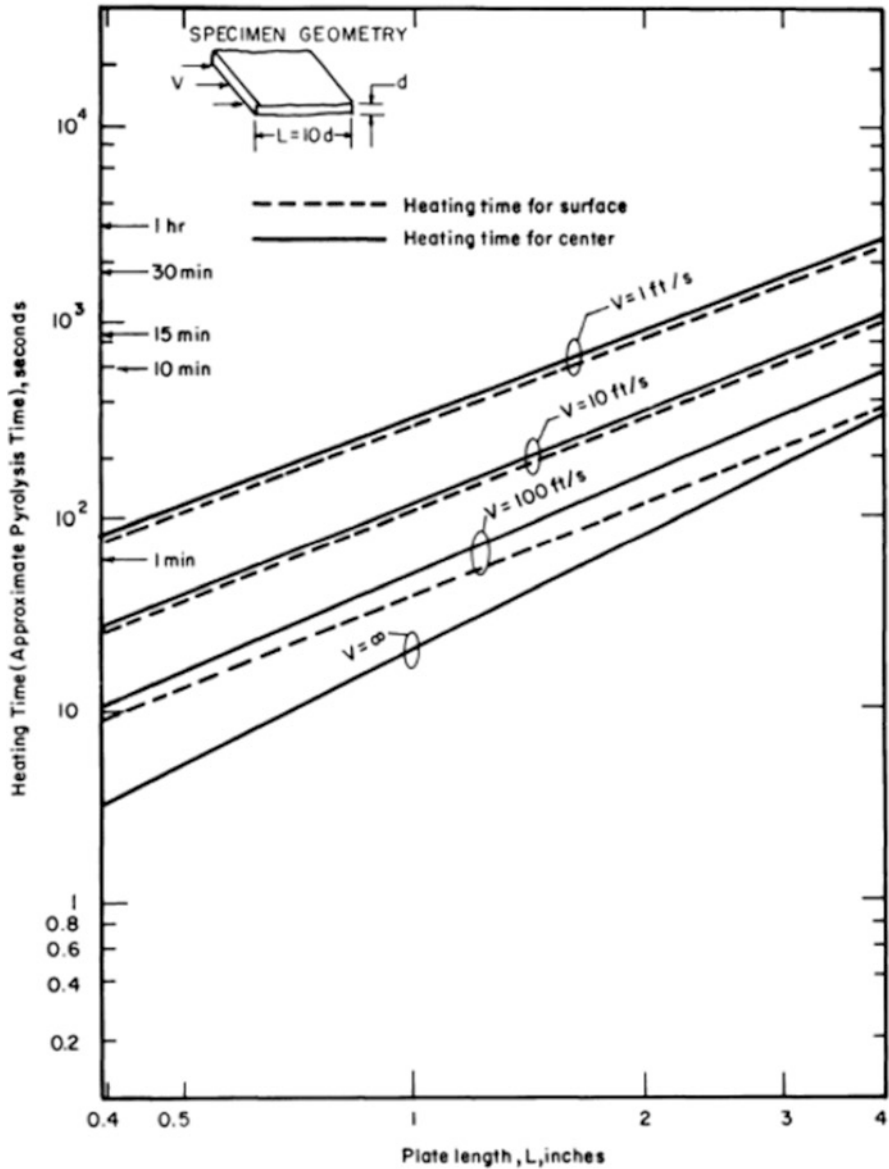


Fig. 6.19 Radiative and convective heating time for a thin plate [7]

6.4.3 Mass Burning

Solid waste is burned in a relatively thick bed at MSWI. Complete combustion occurs at and around the grate in an idealised conceptualisation of the bed processes (after ignition down to the grating line), absorbing the oxygen in the undergrated air to form CO_2 and H_2O .

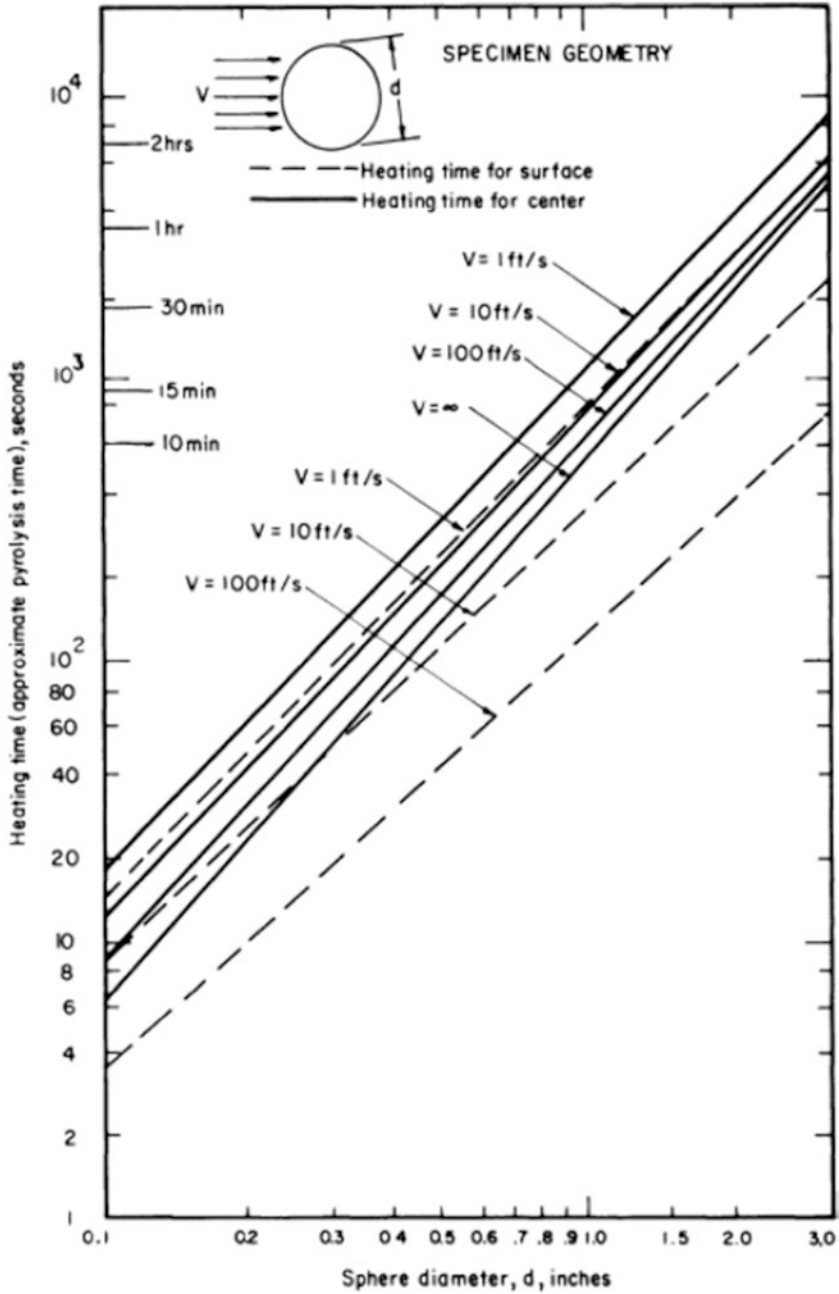


Fig. 6.20 Radiative and convective heating time for a sphere [7]

Table 6.6 Yields of pyrolysis products from different refuse components by weight percentage of refuse^a

Component	Gas	Water	Other liquid	Char (ash-free)	Ash
Cord hardwood	17.30	31.93	20.80	29.54	0.43
Rubber	17.29	3.91	42.45	27.50	8.85
White pine sawdust	20.41	32.78	24.50	22.17	0.14
Balsam spruce	29.98	21.03	28.61	17.31	3.07
Hardwood leaf mixture	22.29	31.87	12.27	29.75	3.82
Newspaper I	25.82	33.92	10.15	28.68	1.43
II	29.30	31.36	10.80	27.11	1.43
Corrugated box paper	26.32	35.93	5.79	26.90	5.06
Brown paper	20.89	43.10	2.88	32.12	1.01
Magazine paper I	19.53	25.94	10.84	21.22	22.47
II	21.96	25.91	10.17	19.49	22.47
Lawn grass	26.15	24.73	11.46	31.47	6.19
Citrus fruit waste	31.21	29.99	17.50	18.12	3.18
Vegetable food waste	27.55	27.15	20.24	20.17	4.89
Mean Values	24.25	23.50	22.67	24.72	11.30

^aRefuse was shredded, air-dried, and pyrolyzed in a retort at 815 °C [6]

Table 6.7 Percentage yields of pyrolysis products from refuse at different temperatures by weight of refuse combustibles^a

Temperature °C	Gases	Liquid (including water)	Char
480	12.33	61.08	24.71
650	18.64	59.18	21.80
815	23.69	59.67	17.24
925	24.36	58.70	17.67

^aFrom reference [7]

CO₂ and H₂O react with char to form CO and H₂ in an endothermic reaction mediated by the water–gas change equilibrium as the gases rise.

The only reaction that occurs above this stage is the pyrolysis of refuse in the hot gases from below. The detailed combustion of MSWI has already been discussed.

6.4.4 Suspension Burning

A particle of refuse is unexpectedly thrown into an atmosphere of hot gases and extreme radiation flux in suspension burning. When in the air, the particle rapidly dries and ignites and then burns in an oxygen-rich environment. The particle may be partially or completely burned while still suspended in the gas stream, depending on the particle shape and weight, the velocity of the gas medium, and the geometry and dimensions of the combustion chamber.

Table 6.8 Effect of heating rate on yields of pyrolysis products and heating value of the pyrolysis gas from newspaper^a

Time taken to heat to 815 °C, min	Yield of air-dried newspaper, wt%				Heating value of gas, kcal/kg of newspaper
	Gas	Water	Other liquid	Char (ash-free)	
1	36.35	24.08	19.14	19.10	1136
6	27.11	27.35	25.55	18.56	792
10	24.80	27.41	25.70	20.66	671
21	23.48	28.23	26.23	20.63	607
30	24.30	27.93	24.48	21.86	662
40	24.15	27.13	24.75	22.54	627
50	25.26	33.23	12.00	28.08	739
60	29.85	30.73	9.93	28.06	961
71	31.10	28.28	10.67	28.52	871

^aReference [7]**Table 6.9** Calorific value of pyrolysis gases obtained by pyrolysing refuse at different temperatures^a

Temperature, °C	Gas yield per kg of refuse combustibles, ^b m ³	Calorific value	
		Gas, kcal/m ³	Refuse combustibles, kcal/kg
480	0.118	2670	316
650	0.173	3346	581
815	0.226	3061	692
925	0.211	3124	661

^aFrom reference [7].^bAt 15 °C, 1 atm.

In general, the furnace's chemistry and heat transfer environment, as well as the specifics of particle characteristics (moisture content, thermal and mass diffusivities, shape factors, and so on), are poorly described, making detailed analysis difficult. Even in the much-simplified case of pulverised coal combustion, many simplifying assumptions must be made in order to predict the flame duration, minimum air requirements, and so on.

For refuse, the second and third stages of the combustion process (heat-up of the dry solid and pyrolysis) may be analysed using Figs. 6.19 and 6.20.

6.5 Economics of Incineration

- There are several conceptual and methodological challenges and pitfalls to be aware of when estimating the MSWI construction and operating costs. First and foremost, it is necessary to differentiate between financial and external costs (the social cost, which is the relevant one for WM policymakers, being the sum of

Table 6.10 Composition of pyrolysis gases obtained by pyrolysing refuse to different temperatures^a

Temperature, °C	Gas composition, volume %					
	H ₂	CH ₄	CO	CO ₂	C ₂ H ₄	C ₂ H ₆
480	5.56	12.43	33.50	44.77	0.45	3.03
650	16.58	15.91	30.49	31.78	2.18	3.06
815	28.55	13.73	34.12	20.59	2.24	0.77
925	32.48	10.45	35.25	18.31	2.43	1.07

^aFrom reference [7].

Table 6.11 Produced pyrolysis gas analysis^a

Waste material	Gas analysis (dry basis), volume %								Heating value ^f	
	H ₂	CO ₂	CH ₄	CO	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	C ₃ H ₈	BTU/ scf	kcal/ scm
MSW ^d	44.47	15.78	6.96	24.76	4.97	1.49	0.66	0.91	421	6750
Sawdust ^c	29.32	12.13	11.04	43.79	3.12	0.36	0.36	NM ^e	398	6380
Chicken manure	35.91	29.50	8.31	21.37	2.22	NM	0.61	NM	308	4940
Cow manure ^d	31.07	20.60	7.70	38.06	1.86	NM	0.31	NM	328	5260
Animal fat	11.57	27.63	18.12	14.72	25.05	NM	2.91	NM	683	10,950
Tire rubber	33.81	15.33	29.09	5.67	12.94	NM	3.17	NM	661	10,600
PVC plastic	41.02	19.06	14.51	20.76	4.02	0.21	0.43	NM	412	6600
Nylon	45.38	6.03	15.47	34.64	0.0	NM	0.0	NM	403	6460
Bituminous coal	46.88	11.68	16.63	21.72	2.08	NM	1.01	NM	435	6980
Sewage sludge (digested)	47.01	22.88	11.22	15.57	3.12	NM	0.21	NM	360	5770

^aFrom reference [7]

^bAverage of five tests

^cAverage of three tests

^dAverage of two tests

^eNM = not measured

^fscf standard cubic feet (60° F, 1 atm); scm standard cubic meter (15 °C, 1 atm)

both). The monetary charges for the design and maintenance of a waste combustion facility are referred to as financial costs. They involve both capital and operating costs, which are likely to be influenced by local conditions and national legislation, though some standardisation is possible.

- Table 6.13 contrasts the findings of some of the most widely cited reference works, which are often published under the auspices of public institutions and national research centres in a variety of countries. All values were translated to € in 2012 using the inflation rate of the country in which the study was conducted, with the assumption that where no information was available, the reference year was the year prior to publication. The \$/€ exchange rate is 1.30. The “gross cost” column represents the overall financial cost, while the “net cost” column includes income from energy and by-product sales. The statistics are incongruent; however, if the analysis is limited to the most recent and the EU background, the figures become more comparable. The gross cost of an up-to-date facility that

Table 6.12 Dry-basis yields from pyrolysis of refuse in weight percentage^a

	C, wt%	H, wt%	O, wt%	N, wt%	S, wt%	Ash, Wt%	Total, Wt%
Feed composition	30.85	3.84	22.32	(0.4)	(0.1)	42.49	100.00
CO	8.01	–	10.68	–	–	–	18.69
CO ₂	4.32	–	11.52	–	–	–	15.84
H	–	2.05	–	–	–	–	2.05
CH ₄	2.25	0.76	–	–	–	–	3.01
C ₂ H ₂	3.22	0.27	–	–	–	–	3.49
C ₂ H ₄	0.95	0.16	–	–	–	–	1.11
C ₂ H ₆	0.43	0.11	–	–	–	–	0.54
C ₃ H ₆	(0.52)	(0.09)	–	–	–	–	0.61
C ₃ H ₈	(0.35)	(0.08)	–	–	–	–	0.43
Liquids	3.45	(0.32)	(0.12)	(0.1)	–	–	3.99
Ash	–	–	–	–	–	42.49	42.49
Char	7.35	–	–	(0.3)	(0.1)	–	7.75
Pyrolysis product totals	30.85	3.84	22.32	(0.4)	(0.1)	42.49	100.00

^aFrom reference [7]. Parentheses indicate estimated values

Table 6.13 Financial cost of MSWI (all values in € as of 2012)

Source	Reference year	Size (kt/yr)	Gross cost (€/t)	Net cost (€/t)	Note
36	2002	648	128	98	Best practice market reference in NL
37	2009	50–500	113–188		Run by private enterprises
	2009	50–500	61–104		Run by municipal associations
38	1987		55–96		WARM model
	2006	80–115	116–126		Configuration typical of SE Asia
		400–600	85–90		Our elaboration assuming economic life = 20 years, r 5%, load factor = 90%
39		300	44–75		
42	2001	200	134		
43	2001	250		79	Based on COWI (2002)
		250		79	

complies with stringent EU regulations and takes advantage of economies of scale is between 100 and 130 € per tonne. The cost of constructing a modern incinerator will range from \$150 million to \$230 million [31].

- The value of recovered capital also affects net costs. These are mostly electricity and ultimately heat in the case of incinerators. Additional revenue can be produced through the recovery of materials (such as metals) and the re-use of ashes as a construction inert.
- Energy prices are subject to their own degree of fluctuation:
- The efficiency of energy recovery is determined by a variety of factors (technology, quality of waste). A plant that treats pre-selected waste will recover 2–3 times more energy and heat than a plant that treats raw waste [32].

- Since the average consumer price in each country is a feature of the technology mix, the market price of electricity can be affected by national market conditions (for example, in Italy, it is significantly higher than in Germany).
- Heat's market value is determined by local conditions, such as the presence of industrial buildings that can easily use heat and/or the viability of district heating. Climate factors clearly matter because they influence heating demand patterns. Many studies support cogeneration, but they assume that recovering heat does not incur additional costs.
- In addition to market rates, potential subsidies must be considered [33, 34]: some countries convert waste to a renewable resource and qualify WtE for green energy subsidies; others impose an incineration levy. In China, the power grid is obligated to buy electricity generated by incinerators at a discounted rate that includes a subsidy [35]. These subsidies should be excluded from the social cost–benefit analysis since they are clearing entries for the collectivity as a whole.

6.6 Case Studies on Incineration Process

6.6.1 *Clean Plaza (Yokote City, Japan) [23]*

Clean Plaza MSWI was established in March 2016 in Yokote City (population: 90,000). It is a small plant ($47.5 \times 2 = 95$ tonnes per day). The plant was planned to have a power generation efficiency of about 20%. The plant's high efficiency is realised with the application of high-temperature and high-pressure boiler conditions of 400°C and 4 MPa. This incineration plant was designed to recover maximum energy even though incinerator capacity was relatively small. High-temperature and high-pressure boiler conditions of 400°C and 4 MPa are used to achieve the plant's high performance. Even though the incinerator capacity was limited, this incineration plant was built to recover as much energy as possible. In addition, the vacuum degree of condensers must be increased in order to improve boiler performance. Improved quality is also aided by the advancement of materials for machinery and piping. As a result, the designed value of 19.6% for gross power generation efficiency was achieved several years ago.

The relationship between the amount of waste incinerated and the amount of power produced was found to be a linear based on actual plant data obtained three years after the start of plant's operation. The unit power generation value is calculated to be 400 kWh per tonne of MSW incinerated. These figures have risen significantly since the first half of the decade of the 2000s. This is a perfect example of how technological advancements can produce impressive results.

The injection of urea into the furnace, a noncatalytic reduction technique that can also save energy, is used to cool flue gas after the boiler operation. With the use of activated charcoal, dioxins and mercury may be eliminated. In April, July, and October 2018, dioxins in effluent gas were 0.0073, 0.00025, and 0.00087 ng-TEQ/

m³N, respectively, which are significantly lower than Japanese flue gas requirements. In the same time frame, dioxin concentrations in bottom ash were below detection limits, while APC residue (fly ash) concentrations were between 0.20 and 0.58 ng-TEQ/g.

Since Yokote City is situated in a region with heavy snowfall in northern Japan, the energy obtained from waste incineration is often used as fuel to melt snow on roads during the winter.

6.6.2 Joetsu Clean Center, Japan [23]

The LCV (8,100 to 15,900 kJ/kg) of MSW to be incinerated at the incineration facility in Joetsu City (population: 190,000) is higher than that of normal MSW in other parts of Japan. The fact that kitchen waste is collected separately in this city contributes to this benefit. The steam conditions at 5.0 MPa and 420°C are better than at other plants, which is a unique feature of this facility. The generators allow for a power output of 6,290 kW, resulting in a generation efficiency of more than 20%. In addition, the facility uses NO_x reduction technology without a catalyst to improve energy recovery performance.

Before being properly disposed of, the final residue (bottom ash and fly ash) is safely handled. Bottom ash is disposed of without treatment, while fly ash is disposed of after being treated with reagents to prevent heavy metal leaching. Cement may also be made with bottom ash as a raw material.

In Japan, there are a variety of similar examples of modern incineration plants that generate a lot of electricity.

- WtE incineration can be completely realised even if the size of an incineration plant is relatively limited (100 to 200 tonnes/day), as seen in this segment. There are numerous examples of small-scale plants that have achieved high power generation efficiency of about 20%.
- High-performance equipment must be mounted in the incineration plant to achieve high productivity in WtE incineration facilities. Furthermore, solid waste should have an incineration-friendly composition. It is also crucial to have a consistent MSW generation and collection system.

6.6.3 MSW in Phuket, Thailand [23]

In Phuket, there are two incinerators. The Ministry of Interior's Department of Public Works began construction on the first incinerator in 1996, and it has been in service since 1999, with a capacity of handling 250 tonnes of MSW per day. However, since 2012, the incinerator's service has been halted due to facility repairs. A private company (PJT Technology Co., Ltd.) has been operating a second

incinerator installed in 2009 with a total capacity of 700 tonnes of MSW per day since 2012.

With a total area of 543 km², Phuket Province is the largest island in the Andaman Sea in southern Thailand. In 2017, the population was 410,211 people, with more than 14 million tourists and visitors. The Phuket City Municipality (CM) is in charge of a waste disposal complex that handled 928 tonnes of MSW per day in 2018 and covers an area of approximately 500,000 m² (including a landfill area of 214,400 m², incinerator plant area of 73,600 m², wastewater treatment area of 52,800 m², and buffer zone of 124,800 m²).

PJT Technology Co., Ltd. reported total revenue of THB 545 million and total expenses of THB 275 million to the Ministry of Commerce's Department of Business Development in 2017. With a capacity of 700 tonnes per day, 320 days of service per year, and a storage capacity of 224,000 tonnes per year, revenue per tonne is expected to be THB 2,433 (tipping fees were estimated at THB 520 per tonne, electricity sales at THB 1,913 per tonne, and expenses at THB 1,226 per tonne). In 1994, the Phuket CM held public hearings on the construction of a stoker-type incinerator power plant, going over its historical history and phase-by-phase growth. Construction on the first incinerator with a capacity of 250 tonnes/day, supported by the Ministry of Interior, began in 1996, and an executive committee on waste management in Phuket Province was created. The first stoker incinerator began operating in 1999, generating approximately 2.5 MW of electricity, but the overall amount of waste (approximately 350 tonnes per day) exceeded the incinerator's capacity, resulting in excess waste being deposited in a landfill site since 2003. In 2007, Phuket CM developed a solid waste management (SWM) master plan, held public hearings for the second stoker incinerator power plant, and awarded PJT Technology Co. Ltd. an investment contract in 2009. The decision of the Phuket CM to award a concessionaire was a watershed moment. The second 700 tonne/day WtE incineration plant began operation in 2012, producing 12 MW of electricity, while the first incinerator was shut down for maintenance in 2012. The Phuket CM applied to the central government for a maintenance subsidy, which was denied, resulting in the suspension of operations at the first incineration plant.

In order for WtE incineration facilities to function properly, a specific amount of waste must be collected. Thailand's Pollution Control Department (PCD), the competent authority for municipal waste policies and technologies, recommends that clusters be established among multiple municipalities (PCD 2017). In 1996, the Phuket Governor and Phuket CM created an executive committee on waste management in Phuket Province with about 18 municipalities, local communities, and environmental NGOs (non-governmental organisations).

Pattaraporn [36] claims that SWM in Phuket has grown continuously since the establishment of the executive committee. In 2007, the executive committee suggested creating an SWM master plan for the city. A memorandum of understanding on SWM signed in 2008 specified that municipalities should collect and transport waste to the disposal centre operated by Phuket CM and pay disposal (incineration and landfill) fees of THB 520 per tonne, but the effectiveness of such cooperation

was contingent on each municipality's ability and policies. However, the plan's implementation was limited in scope.

According to a public official, the scheme was not carried out because no staff was in charge of its execution. The 2014 Phuket SWM Master Plan, which specifically falls under the purview of the Phuket Office of Natural Resources and Environment, is viewed differently. The executive committee's authority and function have also grown. This enables SWM issues to be handled simultaneously. Nonetheless, the effectiveness of these institutions and policies is dependent on the level of understanding among relevant authorities and the general public of the gravity of the problems, as well as their level of engagement and cooperation in implementing changes.

Understandably, the majority of waste in Phuket is organic, with high moisture content, resulting in LCVs and inefficient incineration. Food waste was historically collected and used as livestock feed, especially for swine, in the early days. However, as tourism and urbanisation increased, piggeries were forced to close, and owners were forced to sell their land or relocate to neighbouring provinces where land was much cheaper. As a result of such social changes, surplus food waste has been shifted into the main waste stream, and the proportion of organic components sent to incinerators has nearly doubled from 34% in 1993 to 64% in 2004.

Following the creation of the Phuket SWM master plan in 2007, the Department of Environment Quality Promotion, in collaboration with local governments and non-governmental organisations, initiated public participation initiatives to encourage waste reduction and separation at the source. The development of an organic waste separation model that uses aerobic composting to produce fertiliser and its successful implementation in pilot communities discovered that removing 15% to 20% of organic waste from the main waste stream would raise the LCV of mixed waste to the designed range, maintain combustion efficiency, reduce incomplete combustion emissions, and increase power generation. Waste separation by societies will help to solve both environmental and energy issues.

6.7 An Approach to Design

The ideas underlying the design of an incinerator were uncomplicated and free of the need to apply both technological and value assessments. This section, however, can only scratch the surface of the system design challenge; we will attempt to structure, if not direct in-depth, the design process in general [37–40].

6.7.1 Characterise the Waste

Characterisation of the quantity and composition of the waste is the foremost important factor in deciding whether they are combustible or not. Keep in mind future development as well as the effect of technological and economic developments on organisational trends and decision-making.

6.7.2 Lay Out the System in Blocks

Incineration facilities are often built in sections, with inadequate attention paid to the mating of interfaces between different elements of an incinerator. Remember the term “system.” It should always begin with waste collection and end with ash disposal.

6.7.3 Establish Performance Objectives

Examine current and future regulatory standards for effluent consistency. Determine whether there is a need for volume reduction, residue burn-out, or detoxification. Apply these to the relevant locations in the facility layout.

6.7.4 Develop Heat and Material Balances

Determine the material and energy flow in the waste, combustion air, and flue gases using the techniques introduced earlier in this chapter. Take into account the likely building materials and set appropriate temperature limits. Investigate the effect of differences in waste feed composition and quantity from the “average.” In reality, these out-of-the-ordinary features would usually best describe day-to-day operating conditions.

6.7.5 Develop Incinerator Envelope

The total size of the device can be calculated using heat release rates per unit area and per unit volume. Establish the basic incinerator envelope using burning intensity, flame length and shape, kinetic expressions, and other analysis methods. The final form will be determined by both judgement and these calculations. Make use of the literature as well as the personal experiences of others. Interact with other

engineers, manufacturers, technicians, and designers of other combustion systems that have similar operating objectives or physical configurations. Try to strike a balance between being overly conservative at the expense of being overly conservative and the unfortunate fact that a few of the answers are tractable to conclusive analysis and computation. Speak with device operators in particular. Too often, designers only talk to one another, leaving important insights from direct personal experience unheard and, worse, unasked for.

6.7.6 Evaluate Incinerator Dynamics

Apply the jet evaluation methodology, buoyancy measurements, analytical relationships, and traditional furnace draught and pressure drop evaluation techniques to understand, though insufficiently, the system's dynamics.

6.7.7 Develop the Designs of Auxiliary Equipment

Determine the sizes and specifications of the system's burners, fans, grates, materials handling systems, pumps, air compressors, air quality control systems, and numerous other auxiliary equipment. Again, the caution is to be generous, defensive, and tough. The cardinal rule is to plan for when "it" occurs, not when "it" will happen.

6.7.8 Review Heat and Material Balances

This self-explanatory phase will help to strengthen the systems perspective by following the flows through one component element after another.

6.7.9 Build and Operate

Fortunately, in many situations, nature is kind – reasonable engineering designs will work, but maybe not to standards. Plants constructed with the greatest care and attention to detail will fail. This is a lot of staff.

Glossary Stoichiometry is a section of chemistry that involves using relationships between reactants and/or products in a chemical reaction to determine desired quantitative data.

“Developed and developing countries” refers to the classification of economies used by the World Bank in its World Development Indicators report released in 2016. The word “developed countries” refers to high-income countries and regions, while “developing countries” refers to low-income, lower-middle-income, and upper-middle-income countries and regions.

“Best Available Techniques Economically Achievable” (BATEA) means the effective methods to prevent pollution and, where that is not practicable, generally to reduce emissions in the air from the industrial activities and their impact on the environment as a whole. In the United States, BATEA is an abbreviation of “Best Available Technologies Economically Achievable” with the same meaning.

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