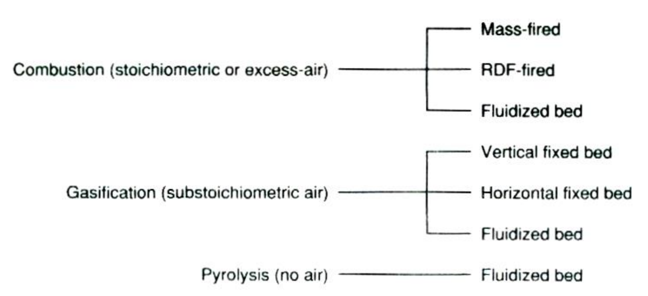
Chapter 13

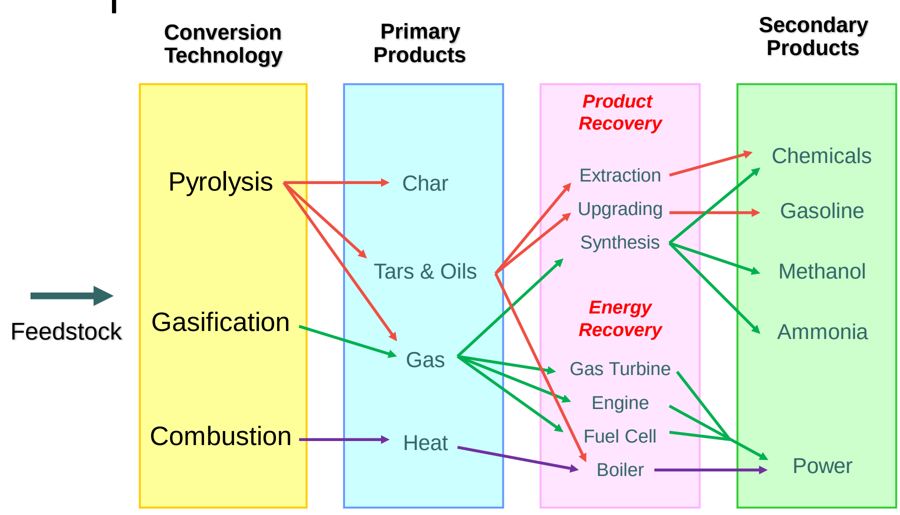
Thermal Conversion Technologies

Fundamentals of Thermal Processing

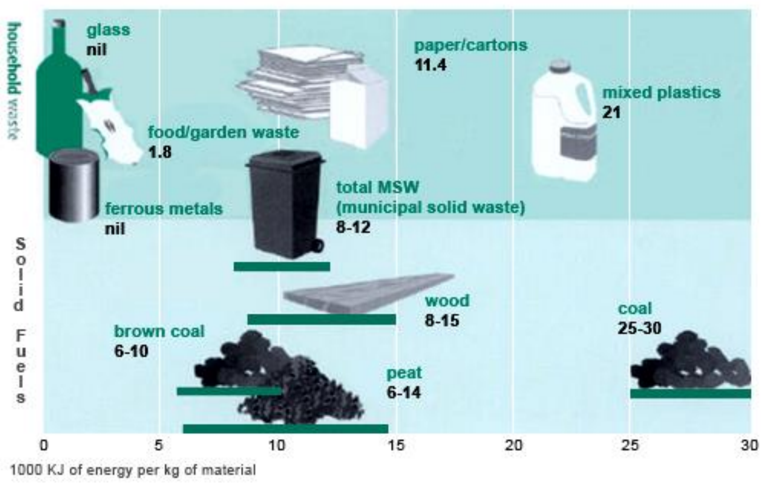
- Thermal processing is the conversion of solid wastes into gaseous, liquid and solid conversion products with the concurrent or subsequent release of heat energy.



Thermal Conversion Technologies



Potential energy of different materials



Combustion

- ***Combustion*** can be defined as the thermal processing of solid fuels by chemical oxidation with stoichiometric or excess amounts of air.
- Because of the inconsistent nature (moisture) of solid waste, it is virtually impossible to combust solid waste with stoichiometric amounts of air.
- ***Excess air*** has to be used to promote mixing and turbelence, thus ensuring that air can reach all parts of the waste.

Combustion

- The use of ***excess air*** for combustion affects the temperature and composition of the combustion products.
- End products include hot combustion gases, composed of primarily of N_2, CO_2 and water vapour (flue gas) and non-combustible residue (ash).
- Energy can be recovered by heat exchange from the hot combustion gases.

Combustion Systems

SW combustion systems can be designed to operate with;

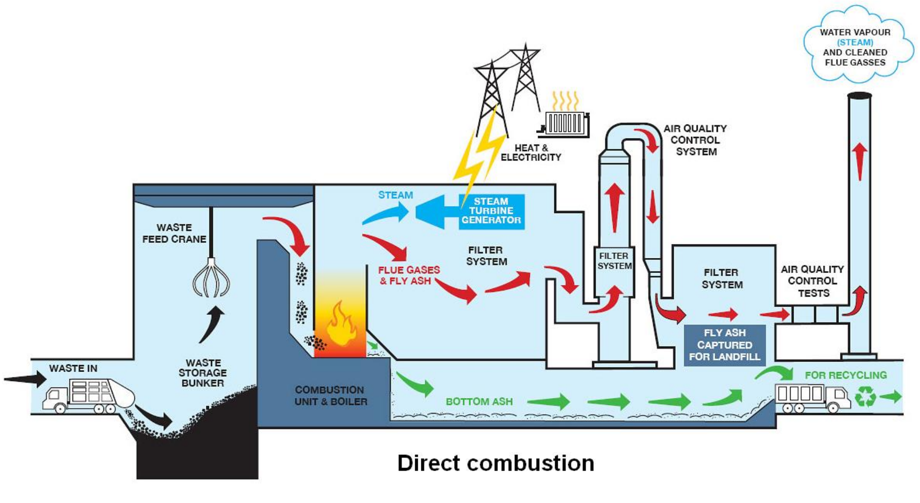
- **Mass-fired** (commingled SW)

  - Minimal processing is given to SW before it is placed in the charging hopper of the system.

- **Refuse derived fuel (RDF)-fired** (Processed SW)

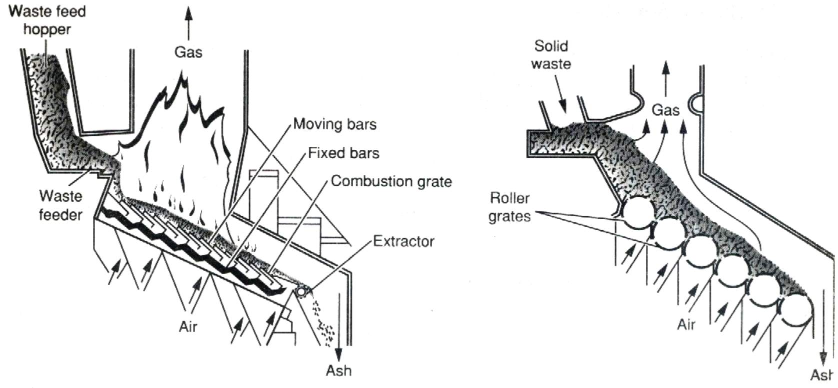
  - Compared to the uncontrolled nature of unprocesses MSW, RDF can be produced with fair consistency to meet specifications for energy, moisture and ash content
  - The RDF can be produced in shredded or fluff form or as densified pellets or cubes

1. Mass-fired combustion

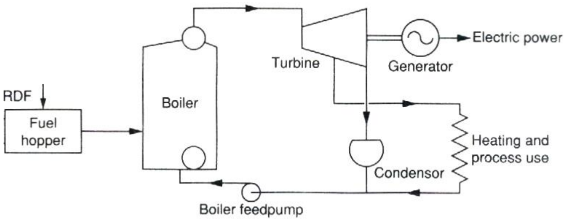


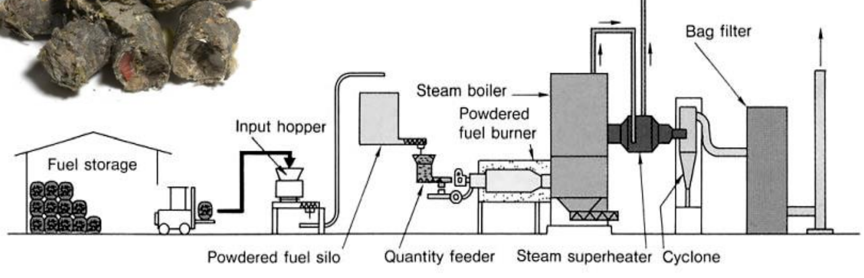
Direct combustion

Grate systems used in mass-fired combustion (Figure 13-3)



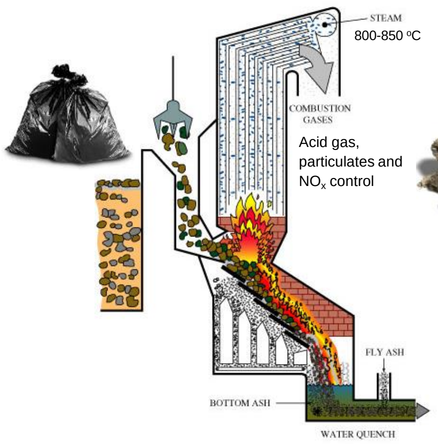
2. RDF-fired boiler system



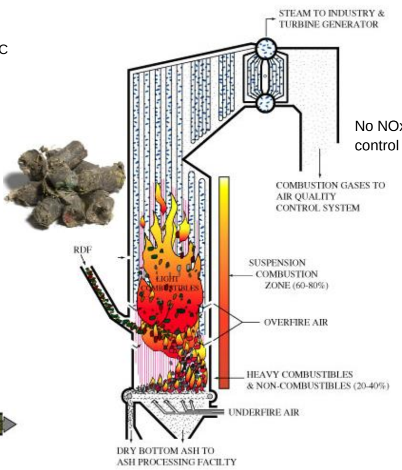


Comparison of combustion systems

Mass-fired combustion



RDF-fired boiler



Fluidized Bed Combustion

- FBC is an alternative design to conventional combustion system.
- It consists of a vertical steel cylinder with a sand bed, a supporting grid plate and air injection nozzles (tuyeres).
- When air is forced up through the nozzles, the bed fluidizes and expands up to twice its resting volume.
- In operation, auxiliary fuel (natural gas or fuel oil) is used to bring the bed up to operating temperature (800-950 ºC).
- After start-up, auxiliary fuel is usually not needed.

Fluidized Bed Combustion

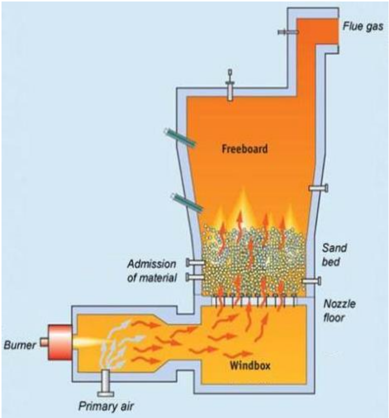


Figure 13-5. Typical fluidized bed combustion (FBC) system

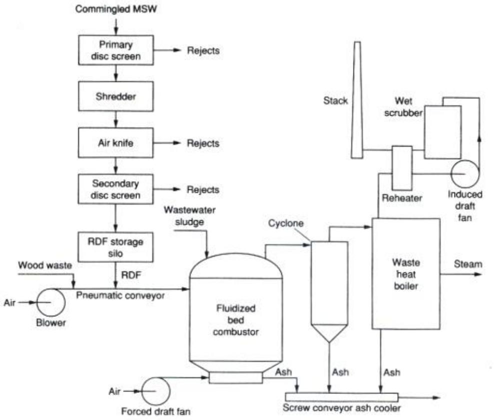


Figure 13-6. Schematic of a FBC for wastewater sludge, RDF and wood waste

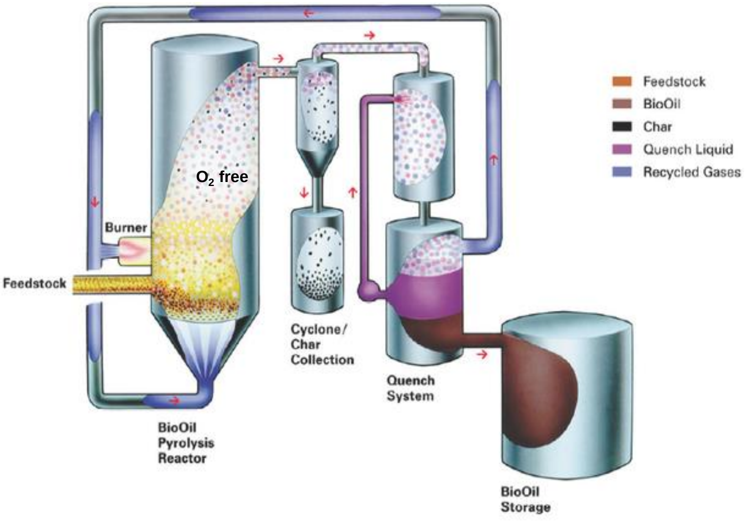
Heat Recovery Systems

- Energy can be recovered from the hot flue gases generated by combusting MSW or RDF by;
  - Waterwall combustion chambers
  - Waste heat boilers
- Either hot water or steam can be generated.
- Steam can be used for both heating and generation of electricity
- When heat recovery is applied, 50 to 100% excess air is adequate, thus reducing size of air pollution control devices.

Pyrolysis

- ***Pyrolysis*** is the thermal processing of waste in the complete absence of oxygen.
- Pyrolysis systems use an external source of heat to drive endothermic pyrolysis reactions in an O_2 free environment.
- In pyrolysis, upon heating, most organic substances split through a combination of thermal cracking and condensation reactions into gaseous, liquid and solid fractions.
- The term ***destructive distillation*** is often used as an alternative term for ***pyrolysis*.**

Pyrolysis system



Products of pyrolysis

Major component fractions resulting from pyrolysis process;

- A **gas** stream, containing primarily **H_2, CH_4, CO, CO_2** and various other gases, depending on organic characteristics of the material pyrolyzed.

- A **liquid** fraction, consisting of a **tar** or **oil** stream containing acetic acid, acetone, methanol and complex oxygenated hydrocarbons. With additional processing, the liquid fraction can be used as a synthetic fuel oil.

- A **char**, consisting of almost pure carbon plus any inert material originally present in the solid waste.

Products of pyrolysis

- The energy content of pyrolytic oils has been estimated to be 5000 kcal/kg.
- Under conditions of maximum gas production (900 ^oC) it has been estimated that the energy contents of the resulting gas (30-33% H_2, 10-11% CH_4, 2-3% C_2H_4 and ~1% C_2H_6) would be about 6200 kcal/m^3.
- Industrial uses of pyrolysis such as production of charcoal from wood, coke and coke gas from coal are very common.
- Pyrolysis of mixed plastic waste has high application potential

Gasification

- ***Gasification*** process has only recently been applied to the processing of SW although it was discovered in 19th century.
- It is the process of partial combustion in which fuel is deliberately combusted with less than stoichiometric air.
- A combustible fuel gas rich in **CO**, **H_2** and some saturated hydrocarbons, principally **CH_4** is generated.
- This fuel gas can then be combusted in an internal combustion engine, gas turbine or boiler under excess air conditions.

Gasification theory

- During ***gasification*** process, five principal reactions occur;

$C + O_2$	$\rightarrow CO_2$	Exothermic
$C + H_2O$	$\rightarrow CO + H_2$	Endothermic
$C + CO_2$	$\rightarrow 2CO$	Endothermic
$C + 2H_2$	$\rightarrow CH_4$	Exothermic
$CO + H_2O$	$\rightarrow CO_2 + H_2$	Exothermic

- The heat to sustain the process is derived from the exothermic reactions, whereas the combustible components are primarily generated by endothermic reactions.

Products of gasification

- Gasifiers operated at atmospheric pressure with air produce;
  - A low calorific value (~1300 kcal/m^3) gas containing 10% CO_2, 20% CO, 15% H_2 and 2% CH_4 with the balance of N_2.
  - A char containing carbon and inerts originally in SW.
  - Condensable liquids resembling pyrolytic oil.
- Air blown gasifiers are quite stable with a fairly constant quality of gas produced over a broad range of air input rates
- When pure O_2 is used instead of air, a gas with an energy content of ~2700 kcal/m^3 is generated

Types of gasifiers

Vertical Fixed Bed Gasifiers

- Simple and relatively low capital costs
- Requires uniform, homogeneous fuels such as densified RDF
- Fuel flow through the gasifier is by gravity, with air and fuel flowing concurrently through the reactor
- End products are low-cal (~1300 kcal/m^3) gas and char
- With simplified control devices low air pollution emissions are achieved.
- Also operated with pure oxygen as an oxidant instead of air

Vertical fixed bed gasifiers

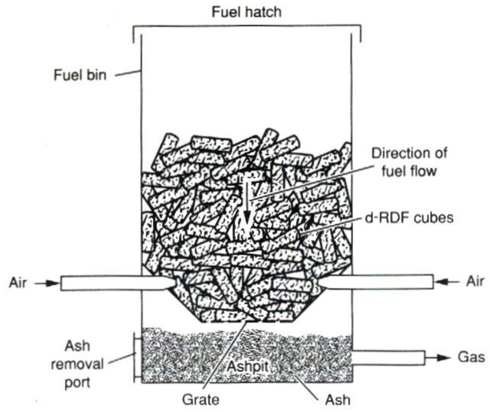


Figure 13-10. Schematic drawing of batch-fed vertical fixed bed gasifier

Types of gasifiers

Horizontal Fixed Bed Gasifiers

- It is the most commercially available type.
- Also known as *starved air combustor*, *controlled air combustor*, or *pyrolytic combustor*.
- Composed of primary and secondary combustion chambers
- In primary combustion, waste is gasified by partial combustion under substoichiometric producing a low-cal gas.
- In secondary chamber, low-cal gas is combusted with excess air at high temperatures (650-900 ^{o}C).

Horizontal fixed bed gasifiers

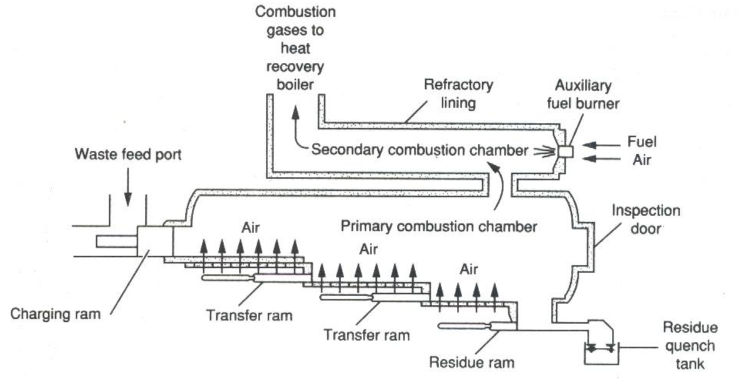


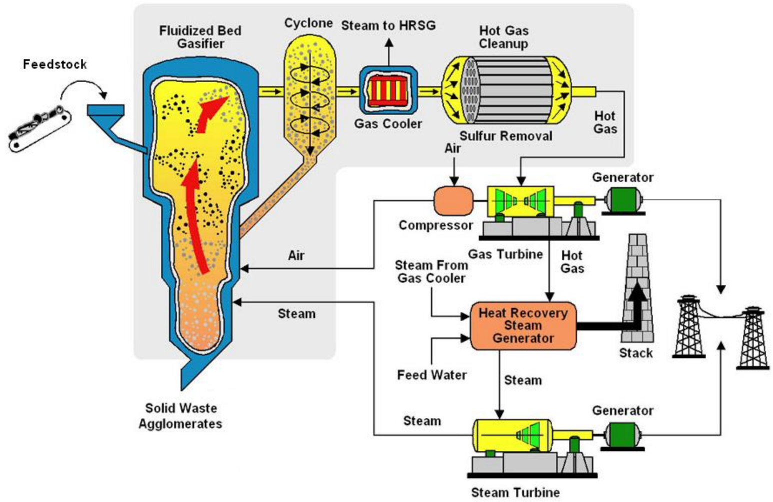
Figure 13-14. Modular combustion unit for MSW and selected industrial waste

Types of gasifiers

Fluidized Bed Gasifiers

- With minimal modifications, a FBC can be operated in substoichiometric mode as a FBG.
- The low-cal gas generated may be used in boilers for the production of steam and electricity.
- Some form of RDF processing to remove metals & other inerts is required to improve performance and reduce air emissions
- Due to their lower emissions, as compared to excess-air combustion systems, FBG may hold the most potential for future development.

Fluidized bed gasifier



Pyrolysis & Gasification

- Both systems are used to convert solid waste into gaseous, liquid and solid fuels.
- ***Gasification*** process is highly exothermic and therefore self sustaining
- ***Pyrolysis*** process is highly endothermic and requires an external heat source.
- Pyrolysis reactions take place in an oxygen free environment and gasification systems use air or oxygen for the partial combustion of solid waste.

Environmental Control Systems

Air Emissions

Criteria pollutants indentified include;

- *Nitrogen oxides* (NO_x) is formed by rxns between N_2 and O_2 in the air used for combustion.
- *Sulfur dioxide* (SO2) is formed by the combustion of fuels containing sulfur.
- *Carbon monoxide* (CO) is formed during the combustion of carbonaceous materials when insufficient oxygen is present
- *Particulate matter* (PM) formed during incomplete combustion of fuel and physical entrainment of non-combustables

Environmental Control Systems

Air Emissions

- *Metals.* MSW is a heterogeneous mixture and contains metallic elements. After combustion, metals are either emitted as PM or vaporized into their gaseous form. Cd, Cr, Hg, and Pb are metals of particular concern from a public health viewpoint.
- *Acid gases.* The combustion of wastes containing fluorine and chlorine leads to the generation of acid gases HF and HCl.
- *Dioxins and furans.* PCDD (polychlorinated dibenzodioxins) and PCDF (polychlorinated dibenzofuran) like cancer-causing organic compounds are formed in thermal processing of MSW

Air pollution control systems

- *PM control*: Electrostatic precipitators, fabric filters, electro-static gravel bed filters
- *NO_x control*: Source separation, combustion control, flue gas treatment
- *SO_2 and acid gas control*: Source separation, wet or dry scrubbing
- *CO and HC control*: Combustion controls
- *Non-criteria pollutant controls*: Source separation, combustion controls, particulate control

Energy Recovery Systems

Principle components used for energy recovery;

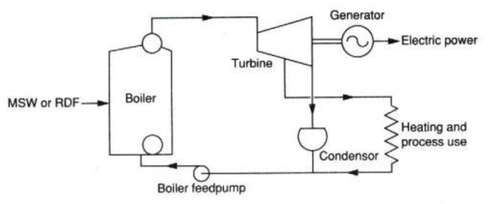
- ***Steam turbines***: Steam is produced in a boiler by burning MSW, RDF or gaseous and liquid conversion products and used to drive the steam turbine which drives an electrical generator. Used in larger systems (10 to 50 MW).
- ***Gas turbines***: It is similar to a jet engine and consists of a compressor to increase the density of gas/air mixture, a combustor, and a turbine connected to an electrical generator to convert hot combustion gases to mechanical energy. Widely used in landfill gas systems.

Energy Recovery Systems

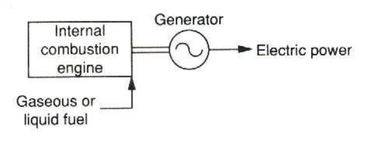
- ***Internal combustion engine***: ICEs using pistons and a crankshaft are an alternative ro gas turbines for gaseous or liquid for the thermal or biological processing of SW. It is a modified version of industrial engines designed for natural gas or propane.
- ***Cogeneration*** is the generation of both thermal and electrical power. Cogeneration systems are used widely in industry to generate electricity and process or building heat at the same time. Applications in energy recovery from SW are limited becuase heat recovered must be used at the site.

Energy Recovery Systems (Figure 13-25)

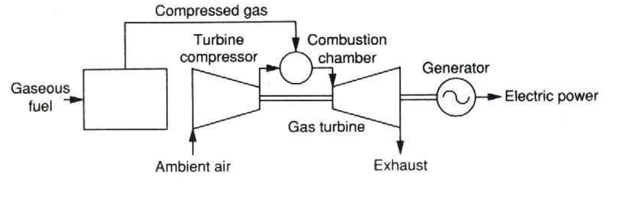
ERS using a steam turbine



ERS using an internal combustion engine

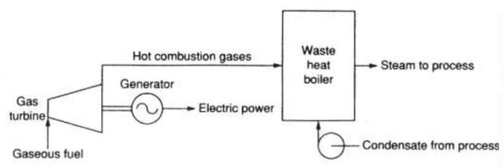


ERS using a gas turbine

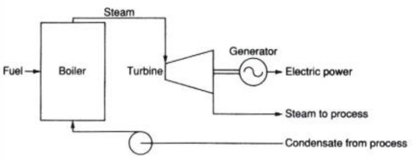


Co-generation systems (Figure 13-26)

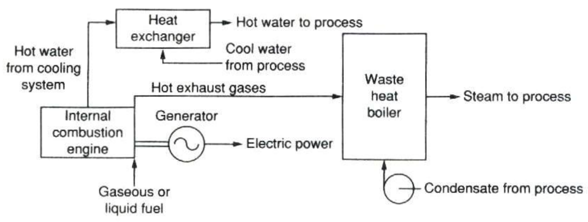
CS using a gas turbine



CS using a steam turbine



CS using an internal combustion engine



Example 13.2 Materials and heat balance for the combustion of solid waste

- Determine the heat available in the exhaust gases from the combustion of 100 ton/d of solid waste with the following characteristics.

Component	**% of total**
Combustible	54.6
Noncombustible	24.0
Water	21.4

Element	**%**
C	27.4
H	3.6
O	23.0
N	0.5
S	0.1
H_2O	21.4
Inerts	24.0

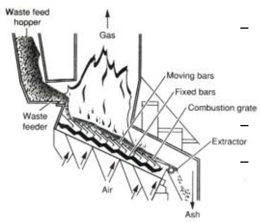
- Theoretical air requirements based on stoichiometry

Carbon : ($C+O_2 \rightarrow CO_2$) 11.52 kg/kg
Hydrogen : ($2H_2 + O_2 \rightarrow 2\ H_2O$) 34.56 kg/kg
Sulfur : ($S + O_2 \rightarrow SO_2$) 4.31 kg/kg

from Ex. 9.2

Example 13.2 Materials and heat balance for the combustion of solid waste

- Assume that the following conditions are applicable:
  - The as-fired heating value of the solid wastes is 12000 kJ/kg
  - The grate residue contains 5% unburned carbon
  - Temperatures: Entering air = 25ºC Grate residue = 450ºC
  - Specific heat of residue = 1.05 kJ/kg.ºC
  - Latent heat of water = 2420 kJ/kg
  - Radiation loss = 0.005 kJ/kJ of gross heat input
  - All oxygen in waste is bound as water
  - The net hydrogen available for combustion is equal to % hydrogen minus 1/8 the % oxygen. This accounts for the "bound water" in the dry combustible material.
  - The heating value of carbon is 32500 kJ/kg
  - Moisture in the combustion air is 1%



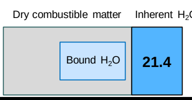
Example 13.2 Materials and heat balance for the combustion of solid waste

Inerts+
5% unburned C

Solution

1. Set up a computation table to determine the weights of elements of the solid waste

Element	%	ton/d
Carbon	27.4%	27.4
Hydrogen	3.6%	3.6
Oxygen	23.0%	23.0
Nitrogen	0.5%	0.5
Sulfur	0.1%	0.1
Water	21.4%	21.4
Inerts	24.0%	24.0
Total		100.0



2. Compute the amount of residue:
   Inerts = 24 ton/d
   Total residue = 24/0.95 = 25.263 ton/d
   C in residue = 25.263-24.0 = 1.263 ton/d
3. Determine the available H and bound H_2O
   $2H_2O \rightarrow 2H_2 + O_2$ Net available H = 3.6-(23.0/8) = 0.725 ton/d
   H in bound H_2O = 3.6 -0.725 = 2.875 ton/d
   Bound H_2O = O + H in bound H_2O
   = 23.0 + 2.875 = 25.875 ton/d

Example 13.2 Materials and heat balance for the combustion of solid waste

4. Set up a computation table to calculate the air required

Element	Air Requirement, kg/d
C = (27.4-1.263)*1000*11.52	301098
H = 0.725*1000*34.56	25056
S = 0.1*1000*4.31	431
Total dry theoretical air	326585
Total dry air including 100% excess	653170
Moisture = 653170*0.01	6532
Total air	659702

5. Determine the amount of H_2O produced from the combustion of available H:

   H_2O = (18 g H_2O)/(2 g H) (0.725 ton/d) = 6.525 ton/d

Example 13.2 Materials and heat balance for the combustion of solid waste

6. Prepare a heat balance for the combustion process

Item	10^6 kJ/d
Gross heat input (100000 kg/d * 12000 kJ/kg)	1200.0
Heat lost in unburned carbon (1263 kg/d * 32500 kJ/kg)	-41.0
Radiation loss (0.005 kJ/kJ * 1200 x10^6 kJ/d)	-6.0
Inherent moisture (21400 kg/d * 2420 kJ/kg)	-51.8
Moisture in bound water (25875 kg/d * 2420 kJ/kg)	-62.6
Moisture from the combustion of available H (6525 kg/d * 2420 kJ/kg)	-15.8
Sensible heat in residue [25263 kg/d * 1.05 kJ/kg ^oC * (450-25)^oC]	-11.3
Total losses	-188.5
Net heat available in flue gases (1200.0 – 188.8) x 10^6 kJ/d	1011.5
Combustion efficiency (1011.2 x 10^6 kJ/d)/(1200.0 x 10^6 kJ/d) x 100%	84.3%

Comment: If the boiler efficiency is 85%, then the overall efficiency would be 84.3% * 85% = 71.6%. This value is consistent with values obtained in MSW combustion systems.