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

- **Conversion Technology**
  - Pyrolysis
  - Gasification
  - Combustion

- **Primary Products**
  - Char
  - Tars & Oils
  - Gas
  - Heat

- **Product Recovery**
  - Extraction
  - Upgrading
  - Synthesis

- **Energy Recovery**
  - Gas Turbine
  - Engine
  - Fuel Cell
  - Boiler

- **Secondary Products**
  - Chemicals
  - Gasoline
  - Methanol
  - Ammonia
  - Power

Feedstock

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Potential energy of different materials

- **Household waste**
  - Glass: 12
  - Paper: 11.4
  - Ferrous metals: nil
  - Food garden waste: 1.2
  - Total MSW (municipal solid waste): 15.2

- **Brown coal**: 6-10
- **Peat**: 6-14
- **Wood**: 8-15
- **Coal**: 25-30

1000 KJ of energy per kg of material
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 turbulence, thus ensuring that air can reach all parts of the waste.

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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 unprocessed 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**

   ![Diagram of Mass-fired combustion](image)
Grate systems used in mass-fired combustion (Figure 13-3)

2. RDF-fired boiler system
Comparison of combustion systems

Comparison of combustion systems

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 °C).
- After start-up, auxiliary fuel is usually not needed.
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 $\text{H}_2$, $\text{CH}_4$, $\text{CO}$, $\text{CO}_2$ 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.

The energy content of pyrolytic oils has been estimated to be 5000 kcal/kg.

Under conditions of maximum gas production (900 °C) it has been estimated that the energy contents of the resulting gas (30-33% $\text{H}_2$, 10-11% $\text{CH}_4$, 2-3% $\text{C}_2\text{H}_4$ and ~1% $\text{C}_2\text{H}_6$) would be about 6200 kcal/m³.

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, H₂ and some saturated hydrocarbons, principally CH₄ 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;
  \[
  \begin{align*}
  C + O_2 & \rightarrow CO_2 \quad \text{Exothermic} \\
  C + H_2O & \rightarrow CO + H_2 \quad \text{Endothermic} \\
  C + CO_2 & \rightarrow 2CO \quad \text{Endothermic} \\
  C + 2H_2 & \rightarrow CH_4 \quad \text{Exothermic} \\
  CO + H_2O & \rightarrow CO_2 + H_2 \quad \text{Exothermic}
  \end{align*}
  \]
- 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 inert 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 °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

Circulating 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.

Combustion-Gasification-Pyrolysis
Environmental Control Systems

Air Emissions

Criteria pollutants identified include;

- **Nitrogen oxides** (NO\textsubscript{x}) is formed by reactions between N\textsubscript{2} and O\textsubscript{2} in the air used for combustion.
- **Sulfur dioxide** (SO\textsubscript{2}) 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-combustibles.

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, electrostatic gravel bed filters
- **NOx control**: Source separation, combustion control, flue gas treatment
- **SO2 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 to 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 because heat recovered must be used at the site.
Co-generation systems (Figure 13-26)