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An Investigation on Thermo Chemical Conversions of Solid Waste for Energy Recovery

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***Abstract*—**Solid waste can be considered as an urban burden or as a valuable resource depending on how it is managed. To meet the rising demand for energy and to address environmental concerns, a conversion from conventional energy systems to renewable resources is essential. For the sustainability of human civilization, an environmentally sound and techno-economically feasible waste treatment method is very important to treat recyclable waste. Several technologies are available for realizing the potential of solid waste as an energy source, ranging from very simple systems for disposing of dry waste to more complex technologies capable of dealing with large amounts of industrial waste. There are three main pathways for conversion of waste material to energy: thermo chemical, biochemical and physicochemical. This paper investigates the thermo chemical conversion of solid waste for energy recovery. The processes, advantages and dis-advantages of various thermo chemical conversion processes are discussed and compared. Special attention is given to Gasification process as it provides better solutions regarding public acceptance, feedstock flexibility, near-zero emissions, efficiency and security. Finally this paper presents comparative statements of thermo chemical processes and introduces an integrated waste management system.

***Keywords*—**Gasification, Incineration, Pyrolysis, Thermo chemical conversion.

I. Introduction

THE disposal of solid waste without adequate treatment generates significant environmental pollution. An effective solid waste management system must be both environmentally and economically safe and suitable. This is an obvious need to minimize the generation of wastes and to reuse and recycle them. The technologies for recovery of energy from solid wastes can play a vital role in mitigating the environmental pollution. Besides recovery of significant energy, these technologies can lead to a substantial reduction in the overall waste quantities requiring final disposal that can be better managed for safe disposal in a controlled manner while meeting the pollution control standards [1]. Waste generation rates are affected by socio-economic development, degree of industrialization, and climate.

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Generally, economic prosperity of many nations and rapid urban population growth resulted in producing a huge amount of solid waste everyday [2]. Reduction in the volume and mass of solid waste is a crucial issue especially in the light of limited availability of final disposal sites in many parts of the world.

Waste generation rates are affected by socio-economic development, degree of industrialization, and climate. Generally, the greater the economic prosperity and the higher percentage of urban population, the greater the amount of solid waste produced [2]. Reduction in the volume and mass of solid waste is a crucial issue especially in the light of limited availability of final disposal sites in many parts of the world.

A number of waste-to-energy conversion pathways are now well-known for realizing the potential of waste as an energy source, ranging from very simple systems for disposing of dry waste to more complex technologies capable of dealing with large amounts of industrial waste. There are three main pathways for conversion of solid waste material to energy – thermo chemical, biochemical and physicochemical. This paper investigates the thermo chemical conversion of solid waste for energy recovery.

II. Thermo Chemical Conversion Processes

Thermo chemical Conversion process involves thermal de-composition of organic matter to produce either heat energy or fuel oil or gas. This process is useful for wastes containing high percentage of organic non-biodegradable matter and low moisture content. Thermo chemical conversion, characterized by higher temperature and conversion rates, is best suited for lower moisture feedstock and is generally less selective for products. The main technological options under this category include Combustion, Pyrolysis, Gasification and Incineration [3, 4]. Figure 1 shows the thermo chemical conversion processes and their products along with energy and material recovery systems.

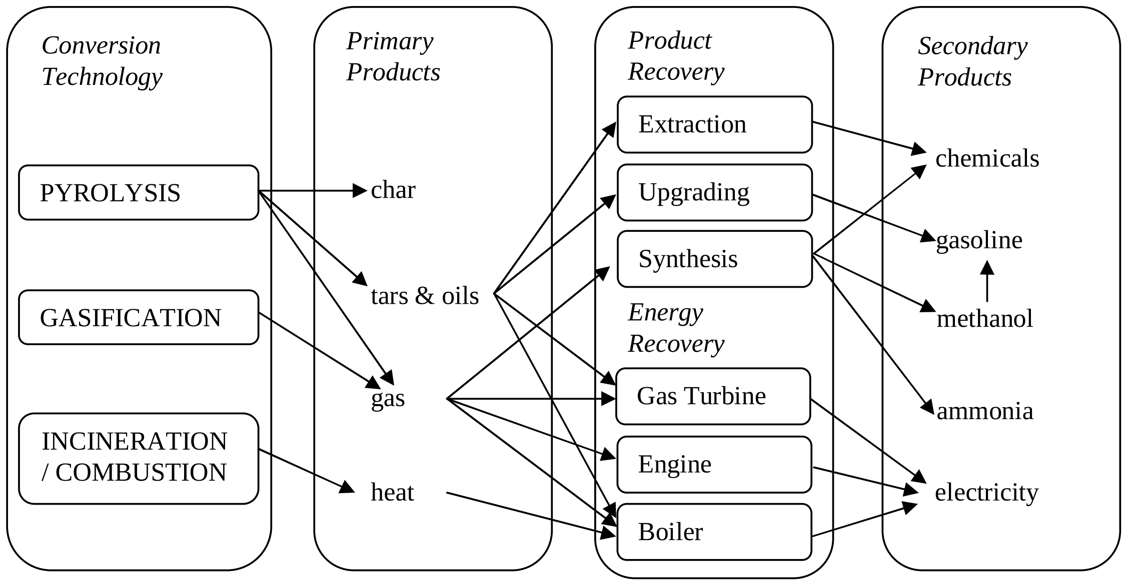

Fig. 1 Thermo chemical conversion processes and products (updated from Bridgwater, 1995)

Combustion or burning is the sequence of exothermic chemical reactions between a fuel and an oxidant accompanied by the production of heat and conversion of chemical species. Incineration is a waste treatment process that involves the combustion of organic substances contained in waste materials. This process maintains a controlled combustion of waste with the recovery of heat to produce steam which in turn produces power through steam turbines. Pyrolysis and Gasification represent refined thermal treatment methods as alternatives to Incineration and are characterized by the transformation of the waste into product gas as energy carrier for later combustion in, for example, a boiler or a gas engine [4 -6].

The main parameters which determine the potential of recovery of energy from wastes (including Municipal solid waste, MSW), are [1, 2]: (a) Quantity of waste and (b) Physical and chemical characteristics (quality) of the waste.

The important physical parameters requiring consideration include: size of constituents, density and moisture content. The important chemical parameters to be considered for determining the energy recovery potential and the suitability of waste treatment through bio chemical or thermo chemical conversion technologies include: volatile Solids, fixed carbon content, inerts, calorific value, C/N ratio (carbon/nitrogen ratio) and toxicity.

In thermo chemical conversion all of the organic matter, biodegradable as well as non-biodegradable, contributes to the energy output. The amount of energy recovered in SW management schemes is very sensitive to the efficiency of the process; that is, the rate at which heat energy contained in fuel is converted into usable energy. The two key factors influencing process efficiency are: (a) electrical efficiency of the power generation technology and (b) amount of heat recovery.

While technology choice for example, Incineration vs. Gasification is an important determinant of process efficiency, the degree to which heat and electricity generated from the energy conversion process are utilized productively is the overriding factor. Different technological options are briefly described and presented in the following section.

III. Technological Options

There are various thermo chemical technological options that can be used for recovery of energy from solid waste. While some of these have already been applied at a large scale, others are under advanced stages of development. Thermo chemical conversion technologies are briefly described below.

A. Gasification

Gasification can be broadly defined as the thermo chemical conversion of a solid or liquid carbon-based material (feedstock) into a combustible gaseous product (combustible gas) by the supply of a Gasification agent (another gaseous compound). The thermo chemical conversion changes the chemical structure of the biomass by means of high temperature. The Gasification agent allows the feedstock to be quickly converted into gas by means of different heterogeneous reactions [7-10]. Gasification process involves:

- Partial oxidation process using air, pure oxygen, oxygen enriched air, hydrogen, or steam
- Produces electricity, fuels (methane, hydrogen, ethanol, synthetic diesel), and chemical products
- Temperature > 700oC
- More flexible than Incineration, more technologically complex than Incineration or Pyrolysis and a high level of public acceptance.

Gasification Principles and Technologies

Generally, the Gasification process includes of the following stages [11-15]:

- Drying. In this stage, the moisture content of the solid waste is reduced. Typically, the moisture content of solid waste ranges from 5% to 35%. Drying occurs at about 100–200 °C with a reduction in the moisture content of the biomass of <5%.
- Devolatilisation / Pyrolysis. This is essentially the thermal decomposition of the solid waste in the absence of oxygen or air. In this process, the volatile matter in the solid waste is reduced. This results in the release of hydrocarbon gases from the biomass, due to which the solid waste is reduced to solid charcoal. The hydrocarbon gases can condense at a sufficiently low temperature to generate liquid tars.
- Oxidation. This is a reaction between solid carbonised waste and oxygen in the air, resulting in formation of CO_2. Hydrogen present in the solid waste is also oxidised to generate water. A large amount of heat is released with the oxidation of carbon and hydrogen. If oxygen is present in substoichiometric quantities, partial oxidation of carbon may occur, resulting in the generation of carbon monoxide.
- Reduction. In the absence (or substoichiometric presence) of oxygen, several reduction reactions occur in the 800–1000°C temperature range. These reactions are mostly endothermic.

Gasification reactor designs have been researched for more than a century, which has resulted in the availability of several designs at the small and large scales. They can be classified in several ways [16]:

- By Gasification agent: Air-blown gasifiers, oxygen gasifiers and steam gasifiers.
- By heat source: Auto-thermal or direct gasifiers (heat is provided by partial combustion of biomass) and auto-thermal or indirect gasifiers (heat is supplied by an external source via a heat exchanger or an indirect process).
- By gasifier pressure: Atmospheric or pressurised.
- By reactor design
  a) Fixed-bed (updraft, downdraft, cross-draft and open-core).
  b) Fluidised-bed (bubbling, circulating and twin-bed).
  c) Entrained-flow: These gasifiers are commonly used for coal because they can be slurry-fed in direct Gasification mode, which makes solid fuel feeding at high pressures inexpensive. These gasifiers are characterised by short residence time, high temperatures, high pressures and large capacities [17].
  d) Stage Gasification with physical separation of Pyrolysis, oxidation and/or reduction zones.

A comparative evaluation of different designs of solid waste gasifiers has been elaborated in Table I.

B. Pyrolysis

Pyrolysis is one of several options for energy recovery from solid waste. It has the advantage of being relatively simple and adaptable to a wide variety of feedstocks and it can produce several usable products from typical waste streams. The features of Pyrolysis include [12, 22]:

- Thermal degradation of carbonaceous materials
- Lower temperature than Gasification (400 – 800oC)
- Absence or limited oxygen
- Products are pyrolitic oils and gas, solid char
- Pyrolysis oil used for (after appropriate post-treatment): liquid fuels, chemicals, adhesives, and other products.
- A number of processes directly combust Pyrolysis gases, oils, and char

A Pyrolysis based process has several advantages when compared to other possible approaches for solid waste resource recovery [12, 22]:

1) it can be used for all types of solid products and can be more easily adapted to changes in feedstock composition than alternative approaches;
2) the technology is relatively simple and can be made compact and lightweight and thus is amenable to spacecraft operations;
3) it can be conducted as a batch, low pressure process, with minimal requirements for feedstock preprocessing;
4) it can produce several usable products from solid waste streams (e.g., CO_2,CO, H_2O, H_2, NH_3, CH_4, etc.);
5) the technology can be designed to produce minimal amounts of unusable by-products;
6) it can produce potentially valuable chemicals and chemical feedstocks; e.g., nitrogen-rich compounds for fertilizers, monomers, hydrocarbons);
7) Pyrolysis will significantly reduce the storage volume of the waste materials while important elements such as carbon and nitrogen can be efficiently stored in the form of Pyrolysis char and later recovered by Gasification or Incineration when needed.

C. Incineration

Incineration is a controlled combustion process for reducing solid, liquid, or gaseous combustible wastes primarily to carbon dioxide, water vapour, other gases, and a relatively small, non-combustible residue that can be further processed or land-filled in an environmentally acceptable manner. The Incineration of solid waste involves a sequence of steps in the primary process, which includes drying, volatilization, combustion of fixed carbon, and burnout of char of the solids, which is followed by a secondary process, the combustion of the vapours, gases, and particulates driven off during the primary process [23, 24].

TABLE I
COMPARATIVE EVALUATION OF DIFFERENT DESIGNS OF SOLID WASTE GASIFIERS [14, 15, 17, 18-21]

Downdraft

- Simple and proven technology.
- High exit gas temperature.
- Producer gas with moderate calorific value and low tar and ash (or particulate) content.
- Suitable for capacities of 20–200 kW.
- High residence time of solids.
- High overall carbon conversion.
- Limited scale-up potential with maximum capacity of 250 kW.

Updraft

- Simple and proven technology.
- Low exit gas temperature.
- Producer gas with moderate calorific value but high tar and ash (or particulate) content.
- Suitable for capacities up to 250 kW.
- High residence time of solids.
- High overall carbon conversion.
- Limited scale-up potential.

Bubbling fluidised bed (BFB)

- High fuel flexibility in terms of both size and type.
- Flexibility of operation at loads lower than design load.
- Ease of operation.
- Low feedstock inventory.
- Good temperature control and high reaction rates.
- In-bed catalytic processing possible.
- Producer gas with moderate HHV but low tar levels and high particulates.
- Carbon loss with ash.
- High conversion efficiency.
- Suitable for large-scale capacities (up to 1MW or even higher).
- Good scale-up potential.
- Good gas–solid contact and mixing.

Circulating fluidised bed (CFB)

- High fuel flexibility in terms of both size and type.
- Flexibility of operation at loads lower than design load.
- Ease of operation.
- Low feedstock inventory.
- Good temperature control and high reaction rates.
- In-bed catalytic processing possible.
- Producer gas with moderate tar levels but high particulates.
- High carbon conversion.
- High conversion efficiency.
- Suitable for large-scale capacities (up to 1MW or even higher).
- Very good scale-up potential.
- Good gas–solid contact and mixing.

Entrained-flow bed

- Relatively complex construction and operation.
- Producer gas with moderate HHV and low tar content.
- Good gas–solid contact and mixing.
- High conversion efficiency.
- Suitable for high capacities (>1MW).
- Very good scale-up potential.

Twin fluidised bed

- Relatively complex construction and operation.
- Producer gas with moderate HHV and moderate tar levels.
- Good gas–solid contact and mixing.
- Relatively low efficiency.
- Suitable for high specific capacities (>1MW).
- Good scale-up potential but relatively complex design.

The factors involves with Incineration are:

- Volume and weight reduced (approx. 90% vol. and 75% wt reduction)
- Waste reduction is immediate, no long term residency required
- Incineration can be done at generation site
- Air discharges can be controlled
- Ash residue is usually non-putrescibles, sterile, inert
- Small disposal area required
- Cost can be offset by heat recovery/ sale of energy

D.Combustion

Combustion of waste has been used for many years as a way of reducing waste volume and neutralizing many of the potentially harmful elements within it. Combustion can only be used to create an energy source when heat recovery is included. Heat recovered from the Combustion process can then be used to either power turbines for electricity generation or to provide direct space and water heating [25].

Some waste streams are suitable for fuelling a combined heat and power system, although quality and reliability of supply are important factors to consider. Combustion involves incinerating organic waste, and substances like plastics and textiles. The incineration process turns the waste into heat, which in turn can be used to generate electricity.

The Combustion reaction requires fuel and oxygen. The oxygen usually comes from the atmosphere. The fuel from waste materials is composed mainly of carbon and hydrogen, but also includes other components such as oxygen, sulfur, chlorine, and nitrogen [26]. To simplify, the combustion reaction can be described as:

C (in the waste) + O_2 --------- > CO_2 + heat

H_2 (in the waste) + O_2 ---------> H_2O+ heat

Perfect combustion can be achieved by mixing the exact amount of oxygen with exactly the right amount of fuel to be combusted. If oxygen is in excess, the combustion system is called fuel lean and the flame is oxidizing. In the case of low levels of oxygen, the system is called fuel rich or reducing. Due to imperfect mixing both of this fuel lean and fuel rich zones exist within the combustion system at the same time. Since each fuel molecule has a chance to meet an oxygen molecule before leaving the combustion chamber, a controlled amount of excess air is supplied and turbulence is induced [23,24].

IV. Discussion and Comparison of Thermo Chemical Conversion Processes

Based on detailed investigation of thermo chemical processes of solid waste, comparative statements have been prepared and presented in Table II. It is clear from Table II that Gasification process provides more affirmative solutions regarding public acceptance, feedstock flexibility, product flexibility, near-zero emissions, efficiency and security. On the other hand, Pyrolysis has fewer air emissions and medium public acceptance. Incineration process is relatively better as it needs minimum land area and the process is noiseless and odourless but it has high capital cost and operation and maintenance (O & M) costs with low public acceptance. Combustion reduces the waste's volume by 85–95 % but emission requirements for MSW combustors have increased rapidly in recent years. Integrated waste management systems (IWMS) is more functional across the world because IWMS promotes sustainable waste management by applying different techniques and at the same time, provide an option to recover resource and energy from the waste stream. IWMS has been considered extensively due to the higher resource recovery rate and potential least environmental impacts from the waste management system. IWMS includes waste sorting, resource recovery, recycling, advance treatment for energy recovery from the waste and disposal of the final residues [5]. Figure 2 shows the integrated waste management system where electricity is produced from Gasification or Incineration processes and recycling of the waste has been done early of the waste treatment to maximize the resource recovery and final disposal goes to the landfill site. IWMS is a system of waste disposal that includes separating materials according to type, and finding the best used for discarded products, which may or may not include depositing in a landfill. IWMS can provide following facilities for an effective waste management through reducing environmental impact and producing energy [28]:

- IWMS can reduce costs and increase recycling practices
- Enhanced service levels in both metropolitan and regional areas
- Improved supplier reporting framework to assist agencies in complying with their Waste Reduction and Purchasing Policy (WRAPP)
- Contributes to a healthier environment: by utilizing the contract of reducing waste and increasing the use of recycling

IWMS not only sort things so that all discarded materials are not going to the landfill, it also helps keep the workers safe. Pre-sorting of many materials through IWMS makes the entire process easier and more efficient.

TABLE II
COMPARATIVE STATEMENT OF THERMO CHEMICAL PROCESSES [7-10, 12, 22,23, 24, 27]

Advantages	**Disadvantages**
Gasification	*Gasification*
• High public acceptance • Feedstock flexibility • Product flexibility • Near-zero emissions • High efficiency • Energy security • Production of fuel gas/oil, which can be used for a variety of applications. • Compared to Incineration, control of atmospheric pollution can be dealt with in a superior way, in techno-economic sense.	• Complex multi-stage process • Up-front processing of feedstock • Syngas must be cleaned/purified • Initial setup is expensive
Pyrolysis	*Pyrolysis*
• Produces few air emissions due to limited use of oxygen • Contamination of air emissions is easy to control because syngas is cleaned after production to rid it of any contaminants • Replaces coal and natural gas as viable fuel sources, causing a reduction in climate change • Produces useful products for multiple applications • Can be easily implemented in CHP systems • More efficient than Incineration (70% vs. 40%) • Pyrolysis plants are flexible and easy to operate because they are modular.	• Generates possible toxic residues such as inert mineral ash, inorganic compounds, and unreformed carbon • Medium public acceptance • Potential to produce a number of possible toxic air emission such as acid gases, dioxins and furans, nitrogen oxides, sulfur dioxide, particulates, etc. • Pyrolysis plants require a certain amount of materials to work effectively
Incineration	*Incineration*
• Minimum of land is needed compared to the dimensions of waste disposal sites. • The weight of the waste is reduced to 25% of the initial value. • The waste volume is reduced to almost 10% of the initial value. • Most suitable for high Calorific Value waste, pathological wastes, etc. • Units with continuous feed and high through-put can be set up. • Thermal Energy recovery for direct heating or power generation. • Relatively noiseless and odourless. • Can be located within city limits, reducing the cost of waste transportation. • Hygienic.	• Low public acceptance • High Capital and O&M costs. • Least suitable for aqueous/ high moisture content/ low Calorific Value and chlorinated waste. • Excessive moisture and inert content affects net energy recovery; auxiliary fuel support may be required to sustain Combustion. • Concern for toxic metals that may concentrate in ash, emission of particulates, SOx, NOx, chlorinated compounds, ranging from HCl to Dioxins. • Skilled personnel required for O&M. • Overall efficiency low for small power stations.
Combustion	*Combustion*
• Reduce the original volume of MSW by 85 - 95 percent • Can only be used to create an energy source when heat recovery is included • Reaction requires only fuel and oxygen • Used to recover a substantial proportion of the energy contained in the waste. • This energy can be used to provide heat and produce electricity.	• In Australia, by contrast, less than 1% of MSW is combusted. • Combustion of MSW is a capital-intensive process, with net costs highly sensitive to the scale of operation and the revenues received for the energy recovered. • The emission requirements for MSW combustors have increased rapidly in recent years.

V. CONCLUDING REMARKS

This paper explores a range of thermo chemical conversion technologies of solid waste. This exhibits that, Gasification process offers considerable energy recovery and reduces the emission of potential pollutants. The main difficulties of solid waste Gasification, especially for MSW, are related to the heterogeneity of wastes. However, Gasification is particularly suitable for many homogeneous agricultural and industrial wastes, such as waste tyres, paper and cardboard wastes, wood wastes, food wastes, etc. Further study is being carried out at CQUniversity regarding thermo chemical process and development of more effective and sustainable IWMS.

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