Advanced Thermal Treatment Technologies for Waste
– Present State of the Art –

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Abstract

An overview is presented on the present state of the art on advanced thermal treatment technologies for waste. Currently Governments and project developers are very interested in environmentally friendly alternatives for incineration (*Mass Burn*). An overview is created of the information that is necessary to compare the performance of different alternatives and subsequently status of several technologies is described. In the past numerous initiatives for advanced thermal treatment of waste have been tried and not come to commercial operation, due to high operational costs and low reliability. Currently several Advanced Thermal Treatment Technologies are in the construction phase and construction and operational experiences have to be anticipated.

1. General Introduction

Advanced thermal technologies for waste conversion, such as pyrolysis, gasification and plasma conversion attract significant attention in view of the following reasons:

- there is a Government supported strive to upgrade the energy performance and the carbon footprint of thermal waste conversion systems.
- the public resistance towards planning of conventional Energy from Waste *Mass Burning* installations leads to a preference for *cleaner* alternatives.

Advanced thermal technologies are increasingly presented to project developers and local govenments as feasible and cleaner alternatives for conventional Energy from Waste technologies. However it is not always clear whether the claims that are made can be sustained.

To make sure that technology selection for thermal waste treatment projects is performed in an objective way, a complete materials – and energy balance of any technology, and a complete overview of operational risks is required. This will help to evaluate technical and financial possibilities – also taking into account possible subsidies for advanced thermal conversion.

In co-operation with the International Solid Waste Association an indicative overview is created on the present state of the art of advanced thermal conversion technologies and on the relation between the different thermal conversiont echnologies. A questionnaire for required technology information is set up. If this required technology information is indeed supplied that will help to compare several technologies in an objective way, thus securing possible project risks.

2. Thermal Treatment Technologies for waste, an introduction

2.1. Relation between pyrolysis, gasification and incineration

To appreciate the relation between incineration and pyrolysis/gasification, basic process parameters and basic process output within the broad scope of thermal treatment of waste are discussed and subsequently the processes are categorized.

The main process parameters within thermal conversion of waste are the oxygen excess (leading to the conversion final product CO_2 and water or to intermediate products) and the temperature within the process.

Basically, as shown in Figure 1, the oxygen excess λ determines whether a process is pyrolysis, gasification or incineration.

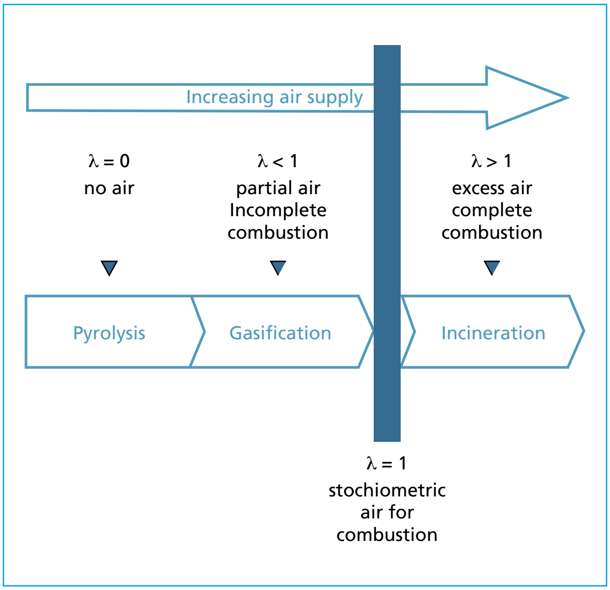

Figure 1:

Relation between air (oxygen) excess and combustion

At pyrolysis or gasification intermediate products, like gas or char are formed that are not combusted and can be combusted afterwards, making pyrolysis and gasification multi-stage processes (as compared to the single stage incineration). After combustion of the intermediate products the end result (namely that all carbon and hydrocarbon content is completely oxydized and is converted into CO_2 and water) is the same like in direct incineration.

In the single stage incineration process the waste starts to dry, subsequently pyrolysis starts, waste is gasified and subsequently at air addition (both primary and secondary) complete combustion takes place between the furnace and first pass of the boiler.

Temperature development within the three processes is different. Pyrolysis is a purely endothermic process. Heat has to be added so that pyrolysis (anaerobic thermal decomposition) takes place. Temperatures range from 300 °C-850 °C.

Gasification on the other hand will in the end lead to some exothermic reactions. Understochiometric amounts of oxygen are added, so that oxidation (exothermic) takes place. At the gasification front, temperatures will vary between 600 and 900 °C.

At incineration complete oxydation takes place and the process will be highly exothermic. The temperatures of combustion will in the firefront be higher than 950-1,000 °C.

A specific treatment is formed by so-called plasma processes.

A plasma Gasification Process is a waste treatment technology that uses electrical energy and the high temperatures (> 2,000 °C) created by an electric arc gasifier. This arc breaks down the organic parts of the waste primarily into elemental gas. A plasma is used most efficiently either in a pyrolysis mode or a pure oxygen gasification mode.

2.2. General status of thermal treatment processes

Incineration processes for waste are utilized since 100 years and can be considered proven technology, whereas both pyrolysis and gasification of waste are to be considered as technologies in development (although some of the processes are in extended demonstration).

In view of pollution aspects of older generation incineration processes (leading for instance to dioxins), public acceptance of incineration (*Mass burn*) processes is low, even though these drawbacks have long been solved and modern incineration processes can be considered clean and energy efficient. This has led to serious consideration of advanced thermal technologies based on pyrolysis or gasification.

Suppliers of such systems claim the following advantages of pyrolysis and gasification in comparison with incineration:

- waste and biomass pyrolysis and gasification potentially offer the possibility to produce a synthesis gas that can be used for a variety of applications such as efficient heat and power production, hydrogen production, production of synthetic natural gas (SNG), production of chemicals like methanol or dimethyl ether (DME), and production of transport fuel (BtL) via Fischer-Tropsch (F-T) synthesis.
- after collection and cleaning syngas can be combusted in a gas engine/ turbine. Because of that, net electrical energy efficiency can be higher in comparison with steam turbine of incineration plants, leading to carbon neutral operation.
- gasification and pyrolysis processes are more suitable for smaller sized installations
- the volumetric flow of flue gases after the pyrolysis/gasification reactor remains smaller

- because of lower flue gas speeds the quantity of fly ashes is smaller
- flue gas cleaning measures (after combustion of cleaned syngas) can be reduced.
- Installations equipped with plasma or high temperature melting furnaces furthermore generate no residues.

3. Comparison of technologies

Technology assessments and comparisons have to be carried out in a similar way, to make sure that like is compared with like. Therefore, the total waste treatment system has to be taken into account. In Figure 2 an overview is given on the total waste treatment system to be taken into account within the assessments.

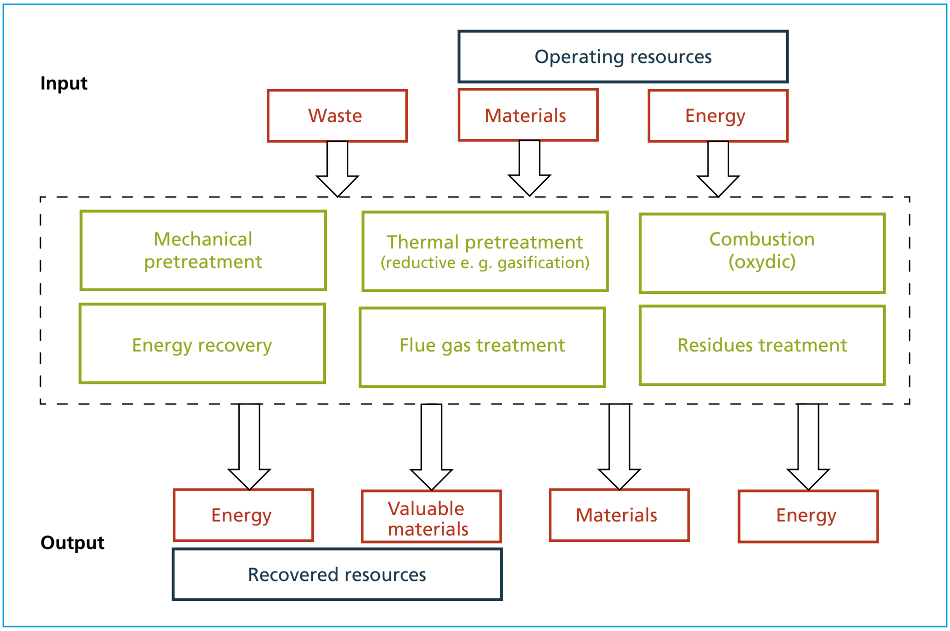

Figure 2: Overview of the unit operations and materials and energy streams within thermal waste treatment technologies

Source: White book on emerging technologies for thermal waste treatment: ISWA working group on Energy Recovery (to be published autumn 2011)

Basically each thermal treatment system for waste consists of the unit operations mechanical pretreatment, thermal pretreatment (generation of intermediate products), final combustion, energy recovery, flue gas treatment and residues treatment. The imputs are waste, energy and other materials streams and the outputs are recoverable (valuable) materials and energy and unrecoverable materials and energy. If systems are described in this way, performance can be compared.

In the special situation that fuels are generated that are not combusted within the waste treatment system, final combustion does not take place and the fuels have to be considered recovered resources.

Furthermore, to be able to assess an advanced waste conversion technologie compared to alternatives, basically the following questions must be addressed for each of the technologies:

- Fitness for purpose
  - Feedstock requirements compared to expected feedstock quality
  - Mass and energy balance (complete, including internal use), including
    - Emissions compared to Permitting requirements
  - Scale of operation per unit
- Operational performance (expected or proven?)
  - Reliability of operation assessment (expected availability)
  - Maintenance requirements
- Reference installations
  - How many reference installations exist and can they be visited
  - Operational track record reference installations
  - Scale of operation reference installations
- Economical assessment
  - Expected capital costs
  - Expected operating costs
  - Expected maintenance costs
  - Tonnage throughput per year
  - Expected income:
    - energy income
    - recycling income (metal streams)
    - required gate fees

Economical aspects will in a lot of cases be priviliged information.

In the following paragraphs an overview is given on the experiences with existing advanced treatment techniques.

4. Pyrolysis technologies

Pyrolysis is the thermal conversion of waste without any input of oxygen. It takes place at relatively low temperatures (450-800 °C) and is an endothermic process.

The process output of a pyrolysis reactor is a sort of synthesis gas with a high heating value, pyrolysis oils and solid residues consisting of a mix of inorganic ash and tar (chars). The less inorganic material a waste contains, the more easy the pyrolysis chars can be used. The pyrolysis gas and oil can potentially be used as a fuel in an engine.

In view of the utilization of pyrolysis chars pyrolysis is either a pretreatment before further gasification / combustion or it should be carried out on biomasses with very low ash contents, to be able to generate clean and consistent products.

Pyrolysis processes for solid waste are for instance supplied by the following providers:

- GEM (Scarborough power plant)
- Compact Power (Avonmouth)
- Thermoselect
- PKA

In several countries pyrolysis of organically contaminated soil within a rotary kiln is state of the art.

Projects of Compact Power are facing substantial delays and have not yet reached startup which was scheduled 1-2 years earlier. Compact Power recently sold its shares. The scale of the existing Avonmouth plant is 7,000 tonnes/year. Further planning is for 28,000 tonnes at Avonmouth (4 lines), and 60,000 tonnes at Wrexham (Wales).

Thermoselect installations in Europe failed and were not taken into production. In Japan a number of plants run that directly supply their gas to the steel industry. Operational costs are not published but are high.

Siemens built a concept comparable to Compact power in the 1990's in Fürth (Siemems Schwel-Brenn process) which proved to be a failure. As a result Siemens stopped the development of Pyrolysis installations.

5. Gasification technologies

Gasification is the thermal conversion of waste with understoichiometric input of oxygen. It takes place at medium temperatures (600-900 °C) and will in the end lead to some exothermic reactions.

The process output of gasification consists of a synthesis gas with a relatively low heating value and an inorganic solid residue stream. In case that the gasification is done with pure oxygen, the synthesis gas has a higher heating value. Syngas can subsequently be used as a fuel, either in a combustion chamber with subsequent steam boiler or in higher efficiency conversion systems such as a gas motor and a gas turbine where electricity is directly generated. Often at lower temperature gasification (below 900 °C), the syngases are loaded with char and in that way potentially contaminate any pipings, gas engine etc.

5.1. Gasification/2 stage combustion

In view of the high contamination of pipings and ducts, there are a number of gasification initiatives that directly combust the synthesis gas in a secondary combustion chamber, even without further gas cleaning. Some others clean the syn gases before further treatment in a boiler at high steam parameters

This 2 stage gasification technique is now supplied by a number of providers such as:

- Energos
- Waste2Energy (cBOS$_{TM}$ technology)
- Biomass Power Ltd (specifically on biomass)
- EPI (Energy products of Idaho)

- INC AS
- TPS
- Novera

The technology is called gasification because of the specific gasification chamber where gas measurements are implemented to monitor gas quality and quantity. Thereby these types of system formally are gasification but could just as well be called two stage combustion.

Gasification with secondary combustion is the only type of gasification that at this moment has been commercially demonstrated and has operated within the European context.

Energos is the market leader in this field with around 7 working installations and a contract in place for an installation in Derbyshire. Waste2Energy with its BOSTM technology is catching up with one commercial scale operation in Dargavel, Scotland and a contract in place for supply of 6 installations to SITA in the UK.

At this moment Energos in the Isle of Wight UK has operated for more than one year. No data are yet known on availability. Data from other Energos plants suggest a yearly availability of 7.500 hrs, which is somewhat lower than for regular Energy from Waste. Furthermore if operated in electricity production modus the electrical efficiency is lower than from a conventional grate fired EfW combustion installation (10-20 % instead of 22-28 %), which may be partly attributed to the smaller scale of operation for gasification plants (5 tons/hr compared to average > 15 tons/hr). To be able to achieve the desired performance the waste has to be pretreated before gasification in the Energos installation.

$cBOS_{TM}$ gasification units in Dargavel Scotland have operated since August 2009 and still have operated too short to be able to evaluate performance. $cBOS_{TM}$ gasification units are very basic installations that are operated batchwise. Waste is inserted and removed manually from 4 parallel gasification chambers that supply one combustion chamber. Due to a wrong boiler design choice and high flue gas temperatures (1,100 °C), boiler failure occurred within months after first startup. New boilers with the correct design have been recently installed and operational experience will be built up. Investment costs for $cBOS_{TM}$ will be lower but operational costs [personnel] higher than for a more advanced gasification-combustion unit such as Energos. Furthermore steam production stability will be possibly more difficult to reach.

Typically these gasification plants are smaller sized than regular combustion lines. Energos Lines have a throughput of 38,000-45,000 tons/yr. $cBOS_{TM}$ lines have a throughput of around 20,000 tons/line/yr, assuming they can realize an availability of 92 %. Waste2Energy have been successful in marketing of this concept as they have closed a contract with SITA to build 6 cBOS installations in the United Kingdom. Several are in planning.

Energos and cBOS gasification units are equipped with a dry or semidry flue gas cleaning system. DeNOx measures are not deemed necessary. WID demands are easily reached

In the UK Novera has supplied technology for the ELSEF project (East London Sustainable Energy Facility-ELSEF). The ELSEF factory is still within its licensing process. The original supplier (Novera) has in 2007 withdrawn from the Defra New Technology Demonstrator Program because of substantial delays in planning process and has sold its shares recently to gasifier developer Bio-Essence. The ELSEF process involves a primary gasification chamber, subsequently gas cleaning and subsequently combustion in a boiler/steam turbine combination, which makes it alike the gasification – combustion processes. For future situations higher quality applications of the gas are foreseen. Based on the planning application the ELSEF factory would lead to the following basic performance specs:

- waste pretreatment necessary
- input waste: RDF with an average CV of 17 MJ/kg
- total throughput 90,000 tons/yr (12 tons/hr)
- output electricity: 8-12 MW (Defra: 8-10; Novera – 12)
- electrical efficiency (for gasification – combustion) 14-21 %

Comparable gasification processes for waste throughout Europe (for instance TPS in Greve) have faced significant problems and have in the end stopped operation in the 90's.

5.2. High temperature gasification

High temperature gasification typically leads to syngas with a lower CV but also with a low tar content. Risks of fouling of piping and fouling and outage of gas turbines is therefore lower than for intermediate temperature gasification. However corrosion risks in the gasification chamber are substantially higher. The latter effect forms an main obstacle for this type of gasification. The ashes from this type of gasification are vitrified and because of that show very low leachability which makes them more fit for utilization. Because of vitrification the energy consumption in the process is high and net energy production relatively low.

Main providers are to be found in Japan.

In Germany KBI provides a high temperature gasification process (also called HTCW technology) with gasification temperatures up to 2,000 °C. No pretreatment of waste is necessary, but a minimum caloric value (CV) of 12 MJ/kg is required to operate the process. This means that this process is not suitable for untreated municipal solid waste which has a CV of 8.5-10. The process is comparable with conventional blastfurnace processes. Experience with waste treatment is not yet on a level that it is proven technology, however experience from blastfurnace operation may support a smoother introduction than for a completely novel process.

- Suppliers are companies like:
- KBI
- Nippon Steel
- Ebara

Basically also Nippo Steel an Ebara processes are based on steel cupola's

5.3. High temperature plasma treatment

A plasma gasification process is a waste treatment technology that uses electrical energy and the high temperatures (> 2,000 °C) created by an electric arc gasifier. This arc breaks down the organic parts of the waste primarily into elemental gas. A plasma is used most efficiently either in a pyrolysis mode or a pure oxygen gasification mode.

For both pyrolysis and gasification of municipal solid waste, often a secondary thermal treatment (plasma/vitrification/high temperature gasification) is used to decompose the solid residue stream and to clean the syngases of any chars and other organic contaminations. In that way syngases are created that are free of organic contaminantst and that are fit for use in a gas engine or a gas turbine. Furthermore the ashes are completely vitrified which leads to low leachability and environmental friendliness.

If a plasma process is used to completely heat and convert the waste, potentially the process is very energy inefficient. The later development in plasma technology is to heat the waste with a gasification installation (for instance fluid bed gasification) and to convert and clean the syn gases with a secondary plasma. In that way the size of the plasma can be subsequently smaller and the energy efficeincy is better. The syn gases after the plasma are reportedly completely free of tar and can after gas cleaning be converted in a gas engine or a gas turbine.

Companies that supply plasma gasification technology to the market are:

- Alter NRG/Westinghouse (Plasma Gasification Process)
- Integrated Environmental Technologies, InEnTec (Plasma Enhanced Melter, PEM)
- Plasco Energy Group (Plasma Arc Gasification)
- ScanArc Plasma Technologies (PyroArc)
- Advanced Plasma Power (APP)
- Solena
- Geoplasma
- InenTec
- ZeGen

Important for the treatment of waste in a plasma enhanced gasification are the additional energy use for the plasma treatment (electrical energy for plasma and eventual enefgy use for oxygen production) and whether pretreatment of the waste is necessary (cost effects and energy effects).

The Alter NRG plasma from Westinghouse is an example for a system that uses the plasma for the complete heating of the waste. The only commercially operating waste plasma gasification installations are Alter NRG. Energy use for the installation is high. Two installations in Japan are built by Alter NRG, one with a througput of 1,25 tons / hr, the other with a throughput of 12,5 tons/hr of Auto Shredder Residues. Total net energy output is 4.3 MW, which is low compared to conventional EfW.

At this moment in the United States and in Europe there is large interest in two stage gasification – plasma systems. Plasco is at the brink of closing contracts in Florida. In Europe Advanced Plasma Power has closed a contract to build installations for landfill mining and gasification of the waste in Belgium. Totally six installations should be built.

6. Performance experience of Gasification and Pyrolysis compared to combustion

An overview of known performance of advanced thermal technologies for waste is given in the table on the following page.

Compared to combustion processes gasification and pyrolysis processes are operated at a considerably smaller scale. Throughputs of 1-5 tons / hr are normal whereas combustion processes at this moment start at around 10 tons/hr and are economically attractive at a scale of around 20-25 tons/hr. At the smaller operational scale of gasification and pyrolysis plants local combined heat and power supply might prove interesting.

For combined heat and power mainly gasification/combustion processes show sufficient operational experience to be a real alternative towards combustion processes.

A significant difference between combustion processes and the gasification and pyrolysis processes is also that gasification and pyrolysis processes are often operated with pretreated waste with a higher CV than regular municipal solid waste. Therefore a combination of gasification and pyrolysis with existing mechanical - biological treatment plants could be an option.

However also combustion processes are possible here and they can be considered more proven than most advanced thermal techniques.

Table 1: Assessment – Performance experiences of advanced thermal technologies

	Pyrolysis	Gasification technologies			Plasma
		Gasification – combustion	Intermediate temperature gasification	High temperature gasification	
Proven technology	0/–	+/0	–	0/–	0/–;
Reliability high	?/– operational problems Siemens/ Thermoselect	+/0 (Energos around 80 % availability)	?/– reported problems with tar formation	?/– No info on operational performance Japanese installations	?/– no info on operational performance Japanese installations
Sufficient experienced providers	–; projects up till yet have not been running operational	0/–; Energos is experienced, Waste2Energy starting up	–; Novera stepped out and sold to Bio-essence	–; KBI not yet proven sufficiently in practice	only two installations running in Japan; projects in development in US, Belgium
Electrical efficiency	unknown	Up to 20 %	Up to 20 % max	Up to 15 % max	Unknown
Fuel flexibility	CV of 10 – 15 MJ/kg; pretreatment necessary	Pretreatment necessary; CV flexibility comparable to incineration	Pretreatment necessary; high CV of > 10 necessary	High CV of > 12 MJ/kg necessary	Pretreatment necessary
Scale	2,5 – 5 tons/hr	2,5 – 5 tons/hr	10 – 12,5 tons/hr	unclear	Up to 25 tons/hr. Experience up to 12 tons/hr
Public acceptance	Low/neutral	Low/neutral	Low/neutral	Low/neutral	Positive

Presently the energy efficiency of incineration techniques is superior towards gasification and pyrolysis. This will only change if techniques are developed and demonstrated to clean the syngases from tar and other pollutions.

The far and recent past has shown that the introduction of gasification and pyrolysis processes is very difficult. The fundamental challenges involved in the technological breakthrough of gasification processes and pyrolysis processes still have to be solved and the solutions have to be demonstrated to the market satisfactorily.

Furthermore developers of gasification and pyrolysis processes are often less financially strong which impairs their possibilities to sustain through periods of market undecisiveness during the process improvements that are necessary for the definite introduction of these techniques.

Therefore for larger initiatives for thermal treatment of untreated waste at this moment conventional combustion techniques still are the only proven technologies. Innovations within combustion even outrun innovations in gasification and pyrolysis if only because of the sheer R&D capacity within the conventional suppliers of grate fired combustion installations.

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