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Municipal Solid Waste as Alternative Fuel – Minimising Emissions and Effluents

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The properties of waste as a fuel, considering municipal and industrial sludge, and various mixtures of solid waste have been analysed. The recent developments in design and technologies of waste treatment for producing heat, power and fuels are evaluated. The use modelling and simulation, CFD, thermal and hydraulic design is explored. The route involving non-thermal treatment is also covered, as anaerobic digestion and microbial fuel cells. The study benefits from Best Available and Best Applicable Technology guidelines developed with the support from the EU. They include criteria of technology selection and procedures optimised choice.

1. Introduction

Energy recovery techniques include thermal treatments as incineration, gasification and other techniques as e.g. anaerobic digestion. Thermal treatments require the burning of waste with recovery of energy. Anaerobic digestion has been used for the treatment of agricultural and sewage sludge. Common treatments are landfilling and incineration. New technologies offer enhanced material recovery, efficient energy recovery and reduced landfill. A proper understanding of waste properties and composition is needed (Best Available and Best Applicable Technology, BREF, 2006). Waste processing has been described by e.g. Ludwig et al. (2003) and Santoleri et al. (2000). The focus is on the 'waste-to-energy' and management approaches of municipal solid waste (MSW). The achievements include low-NO_x burners, improved efficiency, heat exchangers, waste heat recovery systems, new wet scrubbers, dioxin filters and the sewage sludge treatment.

2. MSW properties

The waste composition defines the possible ways of its utilization as an alternative fuel. Chemical analyses and toxicity tests are employed to evaluate the environmental hazard from the waste sludge generated during the biological treatment of urban waste. Mantis et al. (2005) found it richer in aromatic hydrocarbons than the industrial sludge. The total polychlorinated biphenyls content in sludge exceed the proposed EC limit for using sludge as a fuel. Chemical analysis is deriving from two leaching procedures: (a) the EC mild leaching test EN-12457-2 and (b) the US EPA aggressive toxicity characteristic leaching procedure (TCLP) test. The tests resulted in different sludge characterizations from chemical and eco-toxicological points of view. The EN-12457-2 is more sensitive to the environmental risk from sludge disposal.

3. Utilization of MSW

EC Directive 2000/76/EC defined incineration as the thermal treatment of waste with or without recovery of the heat generated. The incineration had been reaching the share of around 20 - 35 % of the MSW produced in the EU countries (BREF, 2006). The average net efficiencies are ~ 18 % of power, ~ 63 % heat production, ~ 43 % CHP. A number of recent technologies and improvements presented Stehlík (2009):

- Incineration takes the form of direct combustion or co-firing. The two main sub-sectors are: MSW and pre-treated MSW incineration (BREF, 2006).
- Deriving secondary fuels is subject to policy making by the EC (Refuse Derived Fuel, 2003). Examples are producing ethanol from carbohydrate containing waste (Kalogo et al., 2007), biodiesel from waste cooking oil (Phan and Phan, 2008) or gaseous fuel from plastic waste (Song et al., 2010).
- A combination of the above options has also been applied, for instance in co-firing refuse derived fuels with coal in cement kilns (Haas and Weber, 2010).

To be used as fuel, MSW is pre-treated, which involves crushing, homogenisation, and mixing with other fuels, including refuse derived fuels (Frey et al., 2003). An important property of the fuel is the particle size - smaller size increases the combustion rate (Haas and Weber, 2010). The heating value of MSW depends on its moisture content. Its magnitude varies and is about half of that for coal. Frey et al. (2003) quoted of 8.3 MJ/kg at 29 % moisture content in Central Europe. Ruth (1998) cited ~ 10.4 MJ/kg at 25 % moisture in the US. The heating value also depends on the oxygen content, the ratio of hydrogen and carbon in the waste. This sector can be divided into sub-sectors (BREF, Waste Incineration, 2006):

- MSW incineration – treating mixed and untreated household, domestic waste including certain industrial, commercial waste and pre-treated municipal waste.
- Sewage sludge incineration – can be separately from other wastes, or combined with other MSW for its incineration
- Clinical waste incineration – arising at hospitals and healthcare institutions.

The incinerated waste is thermally decomposed and corresponding amount of energy is released. The recent point of view considers the incineration rather as a waste processing technology than just a waste disposal. The heart of an incinerator is the combustion chamber. A plant burning the waste at high temperature under controlled conditions can generate enough electrical power as the surroundings. The flow-out is metal and ash removed on conveyor belts. The metal is separated for recycling, the ash for re-processing. The exhaust hot gasses pre-treated to remove pollutants. Advanced filtering systems capture the ash and small particles. Thermal processing of various types of waste is substantially reducing the waste volume and besides that, WTE (waste-to-energy) systems can provide a comparatively clean, reliable and renewable energy. Characteristics of seven types MSW Incineration ash are reviewed (Lam et al., 2010) with focus on the chemical properties and thermal treatment method. The major MSW management options are presented on the Table 1 (Cheng and Hub, 2010).

Table 1: MSW management technology options

Technology	Advantages	Disadvantages
Landfilling	• Universal solution that provides waste disposal; • Relatively low cost and easy to implement; • Complements with other technology options for handling residual waste; • Can derive landfill gas as a by-product for household and industrial uses;	• Requires large land area; cost incurred as landfill expands • Does not reduces MSW volume • Results secondary pollution problems, as groundwater pollution, air. pollution, and soil contamination; • Due to public resistance and space limitation, landfills are often far away, long distance transporting
Composting	• Converts decomposable organic materials into an organic fertilizer; • Reduces the amount of waste to be landfilled and integrates well with landfilling and materials recovery/recycling.	• Costly to implement and maintain; • Has no environmental or economic advantages compared to incineration; • Requires waste size reduction and degree of separation/processing; • Public perception, such as bioaerosol emissions during the composting process, and insects; • Compost may cause soil pollution by heavy metals and pathogens.
Incineration	• Optimal land usage; • Substantial reduction in the volume of waste • Minimal pre-processing of waste; The bottom ash is biologically clean and stable • Heat can be used as energy source for CHP • Can be located near residential areas, reducing cost of transporting;	• More space than other technologies; • High capital, operational and maintenance cost; • Significant operator expertise is required; • Air pollution control equipment is required to treat the flue gas, and the fly ash needs to be disposed in hazardous waste landfills; • Public perception is sometimes negative, primarily with dioxins emission.

3.1 Combustion

Combustors are used for their high availability, flexibility and efficiency. Harmful compounds produced by waste combustion are particulate matter, SO_x, NO_x, HCl, HF, dioxin, furans, and heavy metals. Most of them are removed by specific treatments, neutralization for acid gases, filtration for fly ashes and absorption with activated carbon for dioxins (Ebner and Clayton, 1995) and other micropollutants like metals (Sedman, 1999). Powder emissions must be controlled by fabric filters, NO_x reduction is achieved by ammonia in the post-combustion chamber or in a catalytic reactor.

Traditional technologies for acid gas removal are semi-dry neutralization with $Ca(OH)_2$ and wet scrubbing (Sedman, 1999). All these technologies are dry treatments and not able to ensure pollutant concentrations smaller than the regulatory limits (EU directive 2000/76/CE: 10 mg/Nm^3 HCl, 50 mg/ Nm^3 SO_2). Wet scrubbers are more powerful but produce waste water. Wet scrubbing plants are applied down-steam of dry neutralization with $Ca(OH)_2$ to reduce the amount of acid gases and the waste water production. Consonni et al. (2005) reported a detailed model comparing four alternative strategies for energy recovery from MSW. Stehlík et al. (2000) built a computer model of an incinerator. Liuzzo et al. (2007) investigated the influence of the flue gas recirculation on the electrical efficiency of the plant and demonstrated its positive effects. Grieco and Poggio (2009) showed it as disadvantageous technologies because drying leads to about 50 °C reduction of flue gas temperature. Characteristics of heat transfer equipment and/or heat exchangers used in WTE systems and their specific features are described by Stehlík (2007). An important role is played by CFD simulations. Stehlík (2011) shown practical aspects of selection and design of heat exchangers for industrial applications where polluted flue gas (off-gas) represents one process fluid. The recent development covered thermal degradation, sludge dewatering, combined coagulation/flocculation, adsorption, LCA and exergy analysis, biological denitrification, minimising Carbon Footprint, and analysis of alternative secondary heat.

3.2 Hydrolysis

Hydrolysis means reaction with water. It is a chemical process in which a molecule is cleaved into two parts by the addition of a water molecule. Cheng et al. (2008) studied hydrolysis of biomass waste (fish and chicken waste, hair and feather) to produce amino acids was studied by in sub-critical water, with reaction temperatures 180 - 320 °C and pressures 3 - 30 MPa. The results show the controlling of reaction atmosphere, pressure, temperature and hydrolysis time is important to obtain high yield of amino acid.

3.3 Cryogenics

Deep cryogenics is the ultra low temperature processing of materials to gain their desired structural properties. This can be used as an alternative for the waste treatment. Cryogenic Int in Scottsdale, Arizona, US (Cryogenics Int) has been using a temperature about -196 °C. Low temperature is achieved using a well-insulated treatment chamber and liquid nitrogen. As the price is high it has been used for cutting and separating waste. Jonna and Lyons (2005) gain useful polymer from a post-consumer mixed polymer waste stream consisting primarily of polypropylene and polyethylene.

3.4 Fuels from pyrolysis, gasification, anaerobic digestion

MSW **pyrolysis** and in particular gasification is very attractive to reduce corrosion and emissions. Slagging gasification is an active process for destructing hazardous compounds of various residues. Cl and S species as HCl and H_2S may still occur in the fuel gas yielded. The yielded fuel gas can be used in various applications (lime and brick kilns, furnaces, dryers, steam-raising boilers, gas engines and turbines etc) or as a raw material (syngas, methanol synthesis, fuel production etc.). Malkow (2004) improved waste incineration efficiency to separate the combustion processes pyrolysis and gasification from the actual combustion. Separation is achieved by having a furnace or boiler with different chambers. Waste **gasification** is a thermal and chemical conversion of organic matter in conditions of oxygen deficiency into a low heating value (LHV) gas (4 - 15 MJ/m^3). The process occurs between 750 - 1000 °C. The produced gas is fired in boilers or in combustion engines. If air is used as gasifying medium, the produced gas has LHV (4 - 7 MJ/m^3) due to its dilution by nitrogen (>50%). It is a technology for converting biomass waste into fuels. With air the organic matter converts into low-energy gas, later used in boilers, combustion engines or turbines. The gas contains minute quantities of heavy hydrocarbons, as ethane and ethene, fine particles of charcoal, ash, and tars. It shows lower thermal losses compared with combustion. De Baere and Mattheeuws (2008) presented the **Anaerobic Digestion** (AD) as a biochemical process where, in the absence of oxygen, bacteria break down organic matter to produce biogas. Most organic material can be processed like biodegradable waste materials (waste paper, grass clippings, leftover food, sewage and animal waste). Distinction was made between mesophilic (35 - 40 °C) versus thermophilic (50 - 55 °C) digestion. The first thermophilic plants were dry fermentation in 1992. AD for the organic fraction treatment is a new technique. Material is similar to the compost produced by anaerobic fermentation process combined with additional post-composting step. Rilling et al. (2005) concluded either composting is used for waste containing high amounts of dry matter. AD turned out as a good alternative for treating wet organic waste. It has captured a significant part of the EU market for the biological treatment of the organic fraction with less than 15 % dry solids. Digesters can also be fed with specially grown energy crops as silage. In a digester microorganisms break down biodegradable material in the absence of oxygen. Houdková et al. (2008) focuses on heat and economic aspects of sludge management and compares three alternative technologies. AD can reduce the amount of organic matter which might otherwise be destined for dumping at sea, landfilled or burnt in an incinerator. Although generally more expensive than composting, the process does have the advantage of producing gas for energy recovery and a usable end product.

3.5 Microbial Fuel Cells (MFCs)

MFCs provide new opportunities for the energy production from biodegradable compounds. MFC converts energy available in a bio-convertible substrate directly into electricity. Bacteria switch from the natural electron acceptor as oxygen or nitrate to an insoluble acceptor as the MFC anode. Transfer occurs via membrane-associated components, or soluble electron shuttles. The electrons flow through a resistor to a cathode, at which the electron acceptor is reduced. Direct conversion enables high conversion efficiency. MFCs were explored in the 1970s (Suzuki, 1976) and treating domestic wastewater were presented by Habermann and Pommer (1991). MFCs with enhanced power output have been developed (Liu et al. 2004). It can operate efficiently at ambient, and even at low temperatures. It does not require gas treatment because the MFCs off-gases are enriched in CO_2. It does not need energy input for aeration provided the cathode is passively aerated (Liu .et al., 2004). Different metabolic pathways are used by the micro-organism and determine the selection and performance of specific organisms. If the electrode prices decrease, this technology might qualify as one the best technologies for conversion of carbohydrates to electricity.

3.6 Developments in advanced equipment design: modelling and simulation, CFD (Computational Fluid Dynamics)

Energy cost and environmental standards encouraged cement manufacturers to evaluate replacement by alternative fuels. Clinker burning is suited for various alternative fuels. ASPEN PLUSR is used to model the four-stage preheater kiln system of a full-scale cement plant (clinker production 2900 t/d), using pet coke as fuel. The goal (Kääntee et al., 2004) is to optimise process control and alternative fuel consumption, while maintaining clinker product quality. The dependence of process performance on the amount of combustion air is clearly demonstrated and the energy demand of the process could be predicted for varying fuel mixes. Zitney (2010) described an Advanced Process Engineering Co-Simulator (APECS) for the high-fidelity design, analysis, and optimisation of energy plants. The APECS combines steady-state process simulation with multiphysics-based equipment simulations, optimisation tools, based on CFD. These capabilities enable to optimise overall process performance, as combustors, gasifiers, turbines, and carbon capture devices. Future APECS co-simulation will focus on carbon management by integrating power plant simulations with CO_2 pipeline and reservoir simulation for carbon storage.

4. Conclusions

The overview facilitates the decision making in the area of WTE by analysing the potential uses of waste as fuel. It provides the criteria for selection of convenient waste treatment technology. The most common systems (landfill, incineration), new and emerging technologies have been described, which allow enhanced material recovery, more efficient energy recovery and reduced landfilling. Which technology to apply depends to large extent on the waste properties. Waste streams with less moisture content and lower toxicity are suitable for direct incineration. Increased moisture content or difficulty of obtaining smaller particle sizes, arises the need for waste co-firing with other fuels. Waste with more significant water content require other treatment for obtaining fuels such as anaerobic digestion, fermentation, gasification or hydrolysis. Other waste property is the harmful compounds. Hazardous waste requires specific treatment such as electrostatic filtering for fly ashes, neutralization for acid gas and activated carbon absorption for dioxins remove. These dry treatments technologies are not able to ensure pollutant concentrations smaller than the EU regulatory limits. Wet scrubbers are more powerful to reach the regulatory limits but produces waste water. The key problems of utilising waste are to achieve simultaneously economic, energy feasibility and benefit. The energy value of the process outputs has to be higher than the process inputs. A number of processing steps should be revisited for improving their efficiency and/or immediate product utilisation. MFCs and gasification are crucial technology with the potential to bypass a number of intermediate steps and fuel utilisation efficiencies. The process benefit consists of increasing energy use efficiency of biomass in relation to power generation. Using the gas in gas turbines and gas/steam cycle, higher efficiency is achieved in power production. In comparison with combustion, gasification shows lower thermal losses and better energy usage. Combination of intuitive design, know-how and sophisticated approach based on up-todate computational tools is shown. Developments in advanced equipment design combining with the recent technologies provide the next-generation energy systems.

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