Plasma Gasification as a Viable Waste-to-Energy Treatment of Municipal Solid Waste

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Abstract

This paper provides a review of literature assessing plasma gasification as a technology for the disposal of municipal solid waste (MSW) with a further benefit of energy recovery from the solid waste. While waste-to-energy (WtE) conversion of MSW by means of incineration or gasification is not new, the application of plasma gasification technology as a waste disposal and energy recovery process is relatively new. This paper will describe the technology and provide an assessment of the energy that could be recovered from different waste feedstock. Treatment of MSW by means of waste-to-energy conversion has two objectives: 1) disposal of waste by a process to significantly reduce the volume of waste before final disposal to a landfill or alternatively, used as a building material, provided the remaining ash or slag is not toxic, and 2) recovery of energy from the waste that could be used to generate electricity or be used to serve other energy needs. Although plasma gasification has higher energy input requirements than other WtE means, this technology offers advantages in waste disposal, especially the treatment of hazardous wastes; energy products recovered that offer flexibility to serve energy needs; and less impact on the environment.

Introduction

The development of waste-to-energy plants has increased over the last 30 years as a result of the need to dispose of growing amounts of solid waste and a need to find sustainable energy sources. In the U.S., there are 87 WtE plants handling up to 30 million tons of waste each year converting it into approximately 15 billion kWh of energy. Singapore, Taiwan and Japan also have made use of WtE technology. Approximately 70 percent of Japan’s MSW is processed through WtE facilities. China is also supporting the development of WtE facilities with the Chinese government calling for the construction of 200 WtE facilities by 2020. In Europe, there are approximately 520 operational WtE facilities. Europe, by far, has the largest share at nearly 60 percent of worldwide investments in WtE facilities. Asia accounts for more than 30 percent of worldwide WtE investments and North America accounted for 9 percent.

The traditional WtE technologies have been primarily combustion or incineration plants. Gasification is an emerging WtE technology that converts carbonaceous materials in MSW to carbon monoxide, hydrogen and carbon dioxide under conditions of partial combustion at temperatures around 700º C. This paper is going to describe the emerging WtE technology, called plasma gasification. The technology will be described and compared to incineration and gasification. A model will be employed to compare the energy content of the resulting gas products from the plasma gasification process for various types of waste feedstock. Plasma gasification has many advantages and some disadvantages compared to other WtE methods which will be described. Depending on the objective of developing a particular WtE plant, the plasma gasification technology advantages could outweigh the disadvantages.

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A Brief Overview of Gasification

Before jumping into the discussion of plasma gasification technology, one should first understand the basics of gasification. Gasification is a complex process of converting organic compounds into a mixture of gaseous species that primarily consists of carbon dioxide (CO$_2$), carbon monoxide (CO) hydrogen (H$_2$) and methane (CH$_4$) (Arafat et al., 2013). The main benefit of gasification is the ability to convert biomass into a valuable energy byproduct called synthesis gas, or the short name syngas. The conversion of the biomass to syngas takes place in a combustion-like chamber at high temperatures and in the presence of limited oxygen. Another way to think of gasification is to think of it as a partial oxidation of the biomass in the presence of a controlled amount of oxygen that is less than the required amount for stoichiometric combustion. Part of the biomass is combusted to provide the heat required to gasify the remainder of the biomass and to sustain the gasification process. This process is known as auto-thermal gasification. If the heat energy is provided by an external supply, then the process is known as allo-thermal gasification (Arena, 2011). Plasma gasification is an allo-thermal gasification process that will be described further in the following sections.

Table 1 in the U. Arena 2011 journal article entitled, “Process and technological aspects of municipal solid waste gasification. A review”, provides a good summary comparing the similarities and differences between combustion, gasification and pyrolysis. These three thermochemical treatment processes can be contrasted to each other based on two operating conditions: a) reaction environment and b) temperature. Combustion is an oxidizing reaction where the amount of oxidant is in excess of that required by stoichiometric combustion and the reaction takes place in a temperature range between 850ºC and 1200ºC. Pyrolysis is a thermal decomposition in the absence of any oxidant and takes place in a temperature range between 400ºC and 900ºC. The reaction environment for gasification is one of reduction where the amount of oxidant is less than that required for stoichiometric combustion in a temperature range similar to that for pyrolysis. Understanding these two operating conditions for each of the three thermochemical treatment processes puts each of these processes in perspective to each other. The product from the gasification process is a hot fuel syngas that consists of carbon monoxide, hydrogen and lesser amounts of methane. The syngas at this stage is generally contaminated by pollutants consisting of particulates, tar, alkali metals, chloride and sulphide, (Arena 2011). The syngas needs to be treated in air pollution control equipment before final use in different applications such as fuel for gas turbines to run generators producing electricity or using the hydrogen for fuel in fuel cell generated energy. The carbon monoxide and hydrogen can be further processed through a Fischer-Tropsch process to produce liquid fuels.

Plasma Gasification Technology

Plasma is formed by heating a gas to very high temperatures where the molecules and atoms ionize and is often considered a fourth state of matter. The degree of ionization, described as the proportion of atoms having lost or gained electrons, is mainly controlled by temperature. Plasma is generally neutral, but as the charged particles within it move, they generate electrical currents with magnetic fields. In summary, plasma is a high-temperature ionized gas that is both thermally and electrically conductive.
Plasma gasification, powered by an external energy source, operates at very high temperatures in an oxygen starved environment to decompose input waste material down to elemental molecules. The products from the process are a syngas, and an inert vitreous (glass-like) material, called slag. Plasma technology breaks down nearly all the materials, excluding radioactive elements, to their elemental form. This is where plasma gasification offers significant environmental benefits over conventional gasification. As a result of the very high temperatures, toxic compounds such as dioxins are completely decomposed to harmless chemical elements. Since conventional gasification doesn’t operate at very high temperatures, the remaining ash and char (remaining biomass matter not completely decomposed), may still have to be handled as a hazardous waste in the final disposal. Plasma gasification is a good process for breaking down hazardous waste, with one useful application being the disposal of medical wastes. It also displays lower environmental impacts in terms of air emissions and slag leachate toxicity as compared to other WtE processes, such as incineration. Vitrified slags produced from a variety of waste materials have been shown to have low leachabilities, therefore can be classified as inert waste, which means than can be safely disposed to a landfill or used as building materials, such as ground up to be used in road beds as a filler (Gomez et al., 2008).

The distinguishing architectural feature for a plasma gasification system is the plasma gasification furnace which has two plasma torches at the bottom of the furnace chamber. The plasma torches are powered by an external energy supply. Similar to other gasification systems, the plasma gasification system will have a feeding system, most likely with a shredder to pre-process the waste, equipment to handle the slag (for plasma furnace) or ash and char (for a gasification furnace), syngas treatment system and a monitoring and control system. Figure 1 shows a typical plasma gasification reactor. Figure 2 shows a sequence of thermal treatment process steps that the MSW goes through as it flows from top to the bottom of the plasma gasification furnace. The resulting syngas flows to the top and is collected through the syngas...
exit piping. The slag is collected at the bottom. In addition to controlling the temperature and plasma air, steam is often introduced in gasification to enhance the production of hydrogen gas.

The central component to the plasma gasification system is the plasma furnace and more specifically, the two plasma torches. Thermal plasmas can be generated by many methods, such as, direct current (DC), alternating current (AC), RF and microwave discharges and by laser. For waste treatment processing, the plasma generation is generally accomplished by DC because DC provides a more stable operation, (less flicker generation and noise), better control, lower electrode consumption and lower power consumption (Gomez et al., 2008). The typical configuration of a plasma gasification furnace is that the processed waste feedstock is fed into the sealed plasma furnace from the top. Two graphite electrodes, (in some installations there could be four), extend into the plasma furnace near the bottom of the reactor in a section called the melting chamber. The torches are spaced apart and an electric current is passed through the electrodes creating an electrical arc. A concentric flow of a gas is introduced from the plasma torches where it is ionized in the electric arc forming plasma jets which extend beyond the tips of the torches. The temperature of the plasma jets can reach up to 6000ºC. Air, nitrogen, oxygen, carbon dioxide, argon, steam and helium are gases that have been used to form plasmas, but air is most commonly used due to its low cost (Mountouris et al., 2006; Bowyer and Fernholz). Secondary air, which can be controlled, is fed into the melting chamber from nozzles surrounding the plasma torches as a means to control the gasification process temperature. High-temperature steam can be introduced at the lower part of the gasification reactor, which can also be adjusted by a central control system. The steam has a positive effect on both syngas heating value and syngas yield (Zhang et al., 2012).

Figure 3 provides a slightly wider view of the plasma gasification process by showing the MSW pre-treatment step, the syngas cleaning process step(s), using air pollution control technologies and the final step of using the recovered energy, whether that be for electricity production or liquid fuel production. A drawback to plasma gasification is that a large amount of electricity is required to operate the plasma torches. U. Arena found that the electrical consumption as compared to the gross output energy produced from the conversion of waste, (ie., heating value plus sensible heat of syngas), was on the order of 15 to 20 percent.³ The results from some analyses carried out with various waste feedstock using the GasifEq model, (to be further described in the following section), suggest that the consumption of electricity could be on the

order of 15 to 40 percent of the gross output energy produced. The findings exclude the results from the analysis of food waste which were found to have a much higher consumption of electricity.

**Thermodynamics and Modeling Gasification of MSW**

This section of the paper will provide a general description of the thermodynamic and chemical reactions that occur during the gasification process. Processes that are unique to plasma gasification in reference to conventional or auto-thermal gasification will be underscored. Mountouris et al. represented the general gasification reaction with air as follows, where the solid waste is represented by means of ultimate analysis as $CH_xO_y$. The moisture content of waste is represented by the term $H_2O$. The moles of air and moisture (water) are shown as $m$ and $w$, respectively. The moles of the various gasification products are shown from $n_1$ to $n_7$.

$$CH_xO_y + wH_2O + m(O_2 + 3.76N_2) \rightarrow n_1H_2 + n_2CO + n_3CO_2 + n_4H_2O + n_5CH_4 + n_6N_2 + n_7C$$

In the review of other literature, it was observed that the ultimate analysis of the solid waste could include other constituents, such as nitrogen, sulfur and chlorine. As the equation would suggest, any organic compound in the MSW, in the presence of air and at a certain temperature, will be converted to the seven products shown. CO and H$_2$ are the two main products of interest, and CH$_4$ to a lesser extent, that make of the synthesis or syngas product. Gasification is a complex chemical process that is composed of many chemical reactions and those chemical reactions involve the transformation of the feedstock into intermediate chemical species followed by a transformation of the intermediate species into the final products (Arafat et al, 2013; Arena, 2011; Mountouris et al., 2006).

For plasma gasification, the heat energy from electricity introduced through the plasma torches would show up on the left-hand side of above equation with the reactants. It is this heat energy plus the amount of plasma air, which for gasification processes is less than stoichiometric amount necessary for combustion that is used to control and sustain the chemical equilibrium reactions that will be described shortly. For the conventional or auto-thermal gasification, part of the waste feedstock is combusted in the less than stoichiometric amount of oxygen that generates the heat to sustain the equilibrium reactions.

While gasification consists of many chemical reactions, some endothermic and others exothermic, Arafat et al., 2013; Arena, 2011; and Mountouris et al., 2006, all agree that gasification can be characterized by three equilibrium reactions that are dominant in the gasification process, shown below.

- The Boudouard reaction: $C + CO_2 \leftrightarrow 2CO$ (1) (endothermic reaction)
- The water – gas reaction: $C + H_2O \leftrightarrow CO + H_2$ (2) (endothermic)
- The methanation reaction: $C + 2H_2 \leftrightarrow CH_4$ (3) (exothermic)
Chemical equilibrium equations (1) and (2) can be combined to give the exothermic water gas shift reaction

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (4)$$

In the case of gasification enhanced with steam as a catalyst, the following equilibrium reaction, describing methane decomposition, will become more prominent.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (5) \text{ endothermic}$$

From the general solid waste gasification equation, it can be seen that there are seven unknowns. Seven equations will be needed in order to solve it. Three mass balance equations can be written: (Mountouris et al, 2006)

- Carbon balance: $$1 = n_2 + n_3 + n_5 + n_7$$
- Hydrogen balance: $$x + 2w = 2n_1 + 2n_4 + 4n_5$$
- Oxygen balance: $$y + w + 2m = n_2 + 2n_3 + n_4$$

Where, x and y are the hydrogen and oxygen content in the solid waste, respectively.

Another three equations can be developed from three chemical equilibrium constants (Mountouris et al.).

- $$K_1 = \frac{[CO][H_2]^3}{[CH_4][H_2O]}$$ for methane decomposition
- $$K_2 = \frac{[CO_2][H_2]}{[CO][H_2O]}$$ for water gas shift reaction
- $$K_3 = \frac{[CO][H_2]}{[H_2O]}$$ for the primary water gas shift reaction

The equilibrium constants, ($K_1, K_2, K_3$), can be calculated from the following formula, knowing the Gibbs standard available energy of formation that is tabulated in various references. The tabulated values in various chemical and thermodynamic references are usually provided at standard temperature and pressure (i.e., 25°C and 1 atmosphere) and would therefore need to be corrected to the gasification temperature

$$K_i = e^{-\Delta G^0/RT}$$ where R is the universal gas constant, T is the reaction temperature and $\Delta G^0$ is the Gibbs standard available energy of formation

Taking the natural log of the above equation, it becomes:

$$\ln(K_i) = -\frac{\Delta G^0}{RT}$$

The Gibbs available energy of formation is a function of the enthalpy (H), entropy (S) and temperature (T) and can be written as follows: $$\Delta G = \Delta H - T\Delta S$$
Mountouris et al. solved for the equilibrium constants, representing them as Taylor series as a function of temperature, where the constants in the equations can be found from thermodynamic data tables, (Chemical Properties Handbook), for the reported temperature range.

The seventh equation will be the energy balance equation which can be represented by the conservation of enthalpy. The enthalpy of the reactants has to equal the enthalpy of the products. The energy balance will included the amount of electricity used in the plasmas reactor, as shown in the following energy balance equation:

\[
\sum nH_f^0, \text{reactants} + E_{\text{electricity}} = \sum mH_f^0, \text{products} + \Delta H_f^0
\]

Where, \( H_f^0 \) is the enthalpy of formation of the reactants and products, \( H_f^0 \) is the change in enthalpy due to change in temperature, \( n \) and \( m \) are the number of moles of reactants and products.

Mountouris et al., model gasification using the mass and energy balance equations plus the equilibrium equations, but they also rely on exergy calculations, which are based on energy availability analysis. For more information on the exergy calculations, see the discussion in the Mountouris et al., 2006 paper.

The efficiency of the production of syngas from a plasmas gasification process is obtained by dividing the lower heating value of the produced syngas by the sum of the lower heating value of the waste feedstock and the electricity used to power the plasma gasification torches. The formula for the efficiency, called the cold gas efficiency is given as follows:

\[
\eta = \frac{\dot{m}_{\text{syngas}} \times LHV_{\text{syngas}}}{(\dot{m}_{\text{waste}} \times LHV_{\text{waste}} + \dot{P}_{\text{Plasma}})}
\]

where \( \dot{m} \) = mass flow rate of syngas and solid waste, \( \dot{P}_{\text{plasma}} \) = electrical power for plasma torch.

Mountouris et al. developed a model, called “GasifEq” to model the plasma gasification thermodynamic and chemical equilibrium processes. It was validated with experimental data obtained from literature searches. The GasifEq model results were compared to other models with the results being in relatively close agreement to each other.

In the next section, the GasifEq model will be used to test different compositions of refuse input in order to assess the potential energy that could be recovered and to illustrate the efficiency of the plasma gasification process.

**Energy Recovery Analysis Using the GasifEq Model**

A parametric study was carried out using Mountouris’s GasifEq model to assess the efficiency and the input energy required for plasma gasification of a few categories of MSW. Table 1 provides an ultimate analysis of a few categories of MSW which will be analyzed using the GasifEq model.
To achieve the highest energy recovery from a plasma gasification plant, solid waste should be pre-processed and the groups of waste with the highest heating value, (i.e., those with the largest carbon and hydrogen content), should be sent to the plasma gasification plant as can be seen from Table 1 and the energy recovery results presented in Figure 4. A feedstock consisting of plastics or rubber produces the largest energy recovery per tonne of input. They do require more electricity input than that required for wood or paper, but the energy recovery is higher for plastic or rubber due mainly to their larger heating values which is due to their large content of carbon and hydrogen as seen from Table 1. At the other end of the spectrum, food waste has a low heating value and large moisture content. From Figure 4, one can see that the energy input greatly outweighs the energy that could be recovered. Therefore, to achieve the best energy
recovery for the energy invested in treating MSW via plasma gasification, then the MSW should be pre-sorted to send the high heating value content to the plasma gasification WtE plant.

Figure 5 presents the cold gas efficiency for various waste feedstocks. The cold gas efficiency is the ratio of the heating value of the produced synthesis gases to the heating value of the waste input plus electricity used by the plasma torches. Looking back to Figure 4, one would take the value of the third bar divided by the sum of the values of the first 2 bars for each feedstock to arrive at the cold gas efficiency.

When the syngas products exit the plasma gas furnace, they are hot gases that need to be cooled and then treated to remove air pollutants. The hot gases could be run through a heat recovery steam generation heat exchanger to recovery some additional useful energy in the form of steam that could be used for district heating or to run a steam turbine to generate electricity.

The plasma gasification process is controlled by adjusting the amount of air used in the reactions. Temperature is also a control variable. In addition, the amount of moisture in the waste feedstock influences the efficiency of the gasification process. The next three figures provide sensitivities by varying either the amount of air, temperature or moisture during the plasma gasification process.

As the amount of air increases the cold gas efficiency decreases as a result of the synthesis gases being diluted by the increasing amount of nitrogen introduced with the air, as shown in Figure 6.
Figure 7 shows a small decrease in the cold gas efficiency with increasing temperatures. Although not shown in the figure, the trend can be explained from reviewing detailed results of the concentrations of CO and H$_2$, the heating value of the combined syngas and the input energy requirement in the form of electricity needed to support the higher temperature. As temperature increases, the concentration of CO increases, whereas the concentration of H$_2$ decreases slightly. The overall heating value of the combine syngas increase marginally, but the electricity required to achieve the higher temperature increases substantially, on the order of +40% for a change from 1273K to 1473K. The energy input outpaces the small gain in syngas heating value achieved; therefore the cold gas efficiency decreases as shown in figure 7. Figure 8 shows the influence of moisture in the waste feedstock on the resulting production of syngas and the energy, in the form of electricity, required to achieve the process efficiencies shown. For the mixed waste, additional energy is used to dry the waste feedstock before it can be thermally converted to the synthesis gases, resulting in a reduction of the process efficiency. For the plastic feedstock, the increase in moisture has a beneficial effect to reduce the amount of electricity required with relatively a small loss in the cold gas efficiency. The plastics typically have around 10 to 15 percent moisture content, so the incremental moisture enhances the hydrogen formation slightly and the carbon monoxide decreases slightly, with the overall heating value of the syngas decreasing slightly. Plasma gasification achieves the highest efficiencies for feedstock having a high heating value and low moisture content.

**Plasma Gasification Compared to Other Waste-to-Energy Methods**

Waste-to-energy facilities serve as a means to dispose of MSW that provide two benefits: 1) a reduction in material to be landfilled, and 2) energy recovery. Plasma gasification technology offers advantages over other waste-to-energy processes; however, it does require a large amount of electrical energy input. Table 2 provides a comparison of plasma gasification to gasification and incineration.
Table 2 – Comparison of plasma gasification to gasification and incineration

<table>
<thead>
<tr>
<th></th>
<th>Plasma Gasification</th>
<th>Gasification</th>
<th>Incineration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of reaction</td>
<td>Reducing (oxidant less than stoichiometric) Limited/controlled oxidant</td>
<td>Reducing (oxidant less than stoichiometric) Limited/controlled oxidant</td>
<td>Oxidizing (oxidant larger than stoichiometric, excess air for complete combustion)</td>
</tr>
<tr>
<td>Process temperature</td>
<td>1500°C - 5000°C</td>
<td>400°C - 900°C</td>
<td>850°C - 1200°C</td>
</tr>
<tr>
<td>Produced gases / Energy product</td>
<td>CO, CO₂, H₂, H₂O, CH₄ Waste heat from cooling syngas that could be recovered</td>
<td>CO, CO₂, H₂, H₂O, CH₄</td>
<td>CO₂, H₂O, waste heat that could be recovered</td>
</tr>
<tr>
<td>Energy recovery efficiency</td>
<td>Higher gross energy recovery resulting from complete decomposition to elemental level</td>
<td>Higher from less heat loss due to deficit of air. Not all char broken down as with plasma gasification, therefore not all energy released</td>
<td>Lower resulting from excess air leading to more waste heat up the stack</td>
</tr>
<tr>
<td>Flexibility of use of energy product</td>
<td>Use syngas to power gas turbine for electricity production or use gas for other commercial uses</td>
<td>Use syngas to power gas turbine for electricity production or use gas for other commercial uses</td>
<td>None. Either heat wasted to atmosphere or must use heat to produce steam to drive turbine for electricity production</td>
</tr>
<tr>
<td>Emissions</td>
<td>Less than gasification and incineration; syngas needs to be cleaned using air pollution treatment methods</td>
<td>Less than incineration; syngas needs to be cleaned</td>
<td>Far greater than gasification; air pollution controls required</td>
</tr>
<tr>
<td>Waste</td>
<td>Inert slag; can be used as fill (eg. Road aggregate); 6% - 15% of original volume</td>
<td>Char, Ash</td>
<td>Ash, which must be treated as hazardous waste; approx. 30% of original volume</td>
</tr>
<tr>
<td>Pollutants</td>
<td>Lower levels of CO, NOX, tars. Other pollutants vitrified in slag</td>
<td>PM, tars, NOX, SOX, dioxins, furans, hydrocarbons, CO, char</td>
<td>PM, NOX, SOX, fly ash, ash, heavy metal volatilization</td>
</tr>
<tr>
<td>Input energy requirements</td>
<td>Very high (1200 – 1500 MJ/tonne of waste); 15% - 20% of gross output energy</td>
<td>Auto-thermal; partial oxidation provides heat for sustaining process; approx. 75% - 88% of waste input energy becomes available in output gas</td>
<td>None.</td>
</tr>
</tbody>
</table>

Another comparison that would be helpful would be a comparison of the economics between conventional gasification, plasma gasification and incineration. The economic comparison is
beyond the scope of this paper, but such a comparison should take into account the reduction in tipping fees at landfills, the extension of the useful operating life of a landfill and the air pollution control equipment acquisition and operating costs. The result of an economic comparison may show that the higher energy costs of plasma gasification may be offset by lower costs in the treatment of the remaining slag and the produced syngas. But that would be a conclusion to make once the data analysis is completed.

Conclusion
Plasma gasification offers several benefits over more conventional forms of gasification and especially incineration. Plasma gasification offers better environmental performance through lower emissions, reduced volume of waste, the vitrified slag, which could be either landfilled or serve as filler material, such as in road construction. While the technology does require significant electrical energy input, it can produce, (or recover from the MSW), an energy fuel gas that has energy content that is approximately up to 80% of the input energy value. Plasma gasification is also a very good means for disposing of hazardous wastes. The syngas that is produced can be used to serve a variety of energy supply needs whereas the energy recovered from incineration has to be used to heat water to produce steam to drive a steam turbine to produce electricity. The Rankine cycle for steam-to-electricity production has efficiency on the order of magnitude of 30% to 40%. The syngas from gasification can be used to run higher efficiency integrated combined cycle power plant to produce electricity. The hydrogen syngas could be used for fuel cells or the syngas could be used to make liquid fuel using the Fischer-Tropsch process. Plasma gasification does offer flexibility and a more environmentally friendly means to dispose MSW. If the primary goal is to significantly reduce the volume of waste that would need to be placed in a landfill with a secondary objective of recovering some useful energy, then plasma gasification should be a technology worthy of consideration in the treatment of municipal solid waste.

References


