THERMAL DESTRUCTION OF WASTE USING PLASMA

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SUMMARY: Thermal technologies for the treatment of waste are once again attracting interest, particularly in Europe and North Amerca, as landfill space becomes scarcer and landfill regulations become more stringent. Plasma technologies can be used to destroy waste at high temperatures, using electricity to convert waste into a fuel gas and an inert rock. The Plasma Arc Waste Destruction System's (PAWDS) is used to destroy waste on board ships. The Plasma Resource Recovery System (PRRS) is used to recover energy and produce a vitrified rock from waste on land. As the use of plasma for waste treatment is becoming more widespread, plasma is gaining acceptance all around the world.

1. INTRODUCTION

Thermal treatment of waste is once again attracting attention as a viable alternative to landfill disposal. Thermal treatment reduces the volume of solid waste significantly but suffers from a bad reputation with the public, representing one of the top industries no-one wants 'in their backyard'. Some of this fear stems from a lack of information about the process, but more justified concerns over emissions remain. Depending on the type and age of technology used, potential emissions include dangerous organic molecules such as furans and dioxins, products of incomplete combustion like carbon monoxide, large amounts of particulates as well as acid rain precursors like nitrogen oxides and sulphurous compounds.

Moreover, the management of the large amounts of bottom ash and potentially toxic fly ash can cause significant disposal problems in countries where landfill space is scarce. Today, the technologies needed to remove the pollutants from the stack gas and to clean the ashes are improving rapidly, although they remain quite expensive. A new strategy which can destroy waste at high temperatures is plasma gasification, using electricity to convert waste into a fuel gas and an inert rock.

2. WHAT IS PLASMA?

Plasma is a gas that conducts electricity. Air is the most common gas used, but methane, steam and several inert gases have also been used. In order for air to conduct electricity, it must be subjected to a large differential in electrical potential. This is done between two electrodes which are separated by air. When this potential is large enough, electrons can be pulled from the normally neutral molecules in the air.

These electrons then move with the electric field and impact other molecules, releasing more

Proceedings Venice 2006, Biomass and Waste to Energy Symposium
Venice, Italy, 29 November – 1 December 2006

free electrons at an exponential rate. This phenomenon iscalled an electron cascade and once enough electrons are moving with the electric field, an arc is created between the electrodes. All of this happens within a fraction of a second. In terms of the electrical circuit, the air gap where the arc is created can be seen as a resistance. While going through this resistance, the electrical current releases large amounts of heat. Several technologies have been developed to use this source of heat which can reach temperatures from 5,000 to 10,000ºC.

With plasma, it is possible to treat waste of varying quality such as waste with a high concentration of inorganic material and a very low heating value. In that case, most of the heat necessary for the gasification will come from the plasma and not from the oxidation of the waste.The following sections will describe some existing applications of plasma in thermal waste treatment.

2.1 The plasma torch

A basic plasma torch contains two electrodes, a cathode and an anode, typically made of copper, with small amount of rare metals such as tungsten or hafnium. A gas flows between these two while the voltage is applied. Once "sparked", an arc is created. The flow of high temperature gas, directed out of the torch tip stretches the electric arc, bringing it out of the torch where it can make contact with the waste to be destroyed. Simply put, the plasma torch works like a hair dryer, where the electric arc acts as the heating element and air is pushed through this elements, which heats it up to very high temperatures of more than 5,000 ºC. The flame that exits the torch, referred to as the plasma "plume" is pictured in the following image.

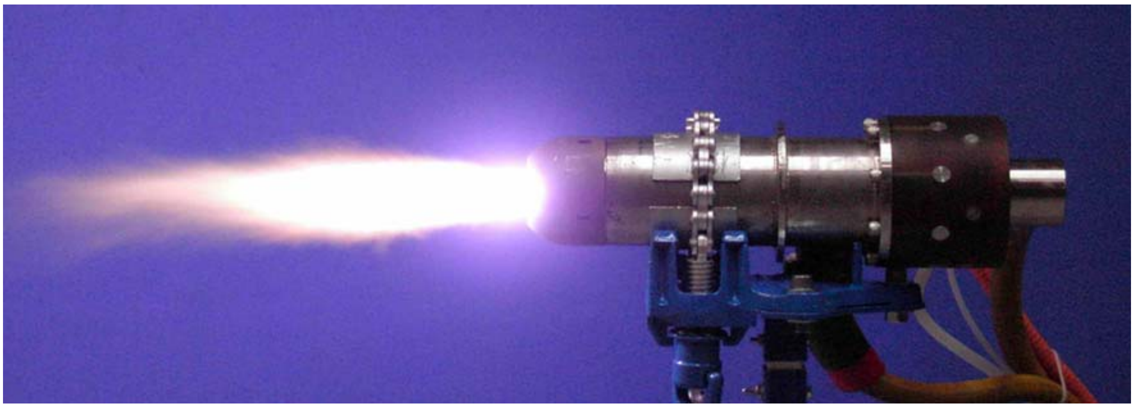

Figure 1 – Pyrogenesis 150 kW Torch

When waste meets the plasma plume in an oxygen deprived environment, it is quickly gasified, creating a syngas from the organic components as well as ash from the inorganics. If the torch is positioned in a way that it can continue to heat the ash, it will turn it into an inert glassy material, known as slag.

2.2 Graphite electrodes

The graphite arc plasma systems use the energy available in an electrical arc by transferring it directly to the material that will be destroyed. A high current (ranging from a few hundred amps to several thousand amps) is directed through long cylindrical graphite electrodes into a furnace, lined with refractory material. The electrical energy typically jumps from an electrode to another (non transferred arc mode) or from an electrode to the waste (transferred arc mode), crossing air gaps in the process. As with the torch, the arcing generates tremendous heat which serves to heat the waste. The temperature in one of these furnaces can attain more than 1,500º C. At this temperature, the inorganic portion of the waste is vitrified (turned to a dense, glassy substance called slag). It is this molten pool of hot slag at the bottom of the furnace that serves as a hot mass of energy, allowing waste to be processed at high feed rates.

3. THE CHEMISTRY OF PLASMA WASTE TREATMENT

The extreme temperatures generated by plasma, when applied to materials such as waste, result in many possible reactions such as combustion, pyrolysis, gasification and vitrification. The end result depends on the nature of the material and on the surrounding conditions, such as the amount of oxygen in the atmosphere where the plasma treatment is occurring. The following section describes the vitrification of inorganic materials as well as the gasification of organic materials.

3.1 Vitrification

Vitrification is the process whereby inorganic components such as silicate melt into a viscous liquid which traps heavy metals into a solid matrix once solidified. The vitrification process converts the inorganic components into a solid rock which will not leach and can therefore be used as construction material. Heavy metals or toxic elements present in the waste are locked in a silicate matrix and are highly resistant to leaching to the environment.

Since the vitrified silicate rock typically has a density of 2.5 times the density of water compared to less than 0.5 for ash from more conventional incinerators, the process of vitrification allows for a significant volume reduction, typically of more than 5 to 1 for ash and more than 50 to 1 for solid waste.

3.2 Gasification and combustion

Plasma can be used in gasification to break down waste into simple gaseous molecules such as carbon monoxide and hydrogen. Although gasifiers such as fluidized bed systems have existed for many years, the heat in plasma allows the use of low energy fuels, such as household and industrial waste which often could not sustain their own gasification without additional fuel.

Gasification is the thermal degradation of carbon based organic materials into a gas at high temperatures (400ºC to 1500ºC). This process is carried out in an oxygen starved environment, preventing the combustion of carbon to CO_2. (When no oxygen is present at all, the process of breaking down large molecules into smaller ones by heat, not by flame, is called pyrolysis. When small amounts of substochiometric oxygen are present, the process is called gasification.)

The following reactions occur in gasification with substochiometric oxygen present (to prevent full combustion).

The partial oxidation of Carbon into CO

$$C + \frac{1}{2} O_2 = CO$$

This reaction is exothermic and releases 110 kJ of energy per mole of carbon. For this reaction to occur there must be available oxygen in diatomic gaseous form.

The partial oxidation of carbon can also occur by using oxygen from water or steam through the following reaction.

$$C + H_2O = H_2 + CO\ )$$

This reaction is endothermic and must absorb energy from the gasifier environment to take place. Therefore, the amount of water or steam fed to the gasifier must be controlled to avoid cooling down the reactor too much.

The water – gas shift reaction also occurs in gasifiers.

$$CO + H_2O = CO_2 + H_2$$

The hydrogasification (also called methanation) reaction also produces methane from carbon.

$$C + 2H_2 = CH_4$$

However, because of the high temperatures involved in a plasma gasification system, the methanation reaction is not thermodyncamically favored.

The gas produced by gasification, called a syngas, synthesis gas or producer gas, consists mainly of CO and H_2 which are both in a reduced state (they are essentially a fuel) and can undergo further oxidation (combustion) to release energy.

Unfortunately, the material fed to the gasifier rarely contains only carbon and hydrogen. There are usually other elements present, such as sulphur, chlorine and nitrogen. The key to predicting what these elements will turn into during the gasification is to consider that the gasifier chamber is operating under a reducing atmosphere, meaning that elements will exit in their most reduced form. For example, with limited oxygen present, the vast majority of sulphur present will come out as hydrogen sulphide (H_2S) gas, while virtually no SO_2 will be produced.

The same goes for chlorine, which mainly forms gaseous HCl. These gases leave the gasifier as contaminants in the syngas and must be cleaned out before the energy in the gas can be used to produce electricity, either by a boiler or internal combustion engine. The components of the syngas can also be used to make other chemicals, such as methanol, formaldehyde and fertilizers.

Depending on the operating temperature of the gasifier, other side products may be formed. For example, sulphur can form carbonyl sulphide (COS), carbon disulfide (CS_2) and thiols (R_2C-SH). The production of these molecules can be significantly reduced if the gasifier is operated above 1,100ºC. In a plasma gasification system, the temperature is typically above 1,100°C, wich reduces the production of the problematic molecules.

There are several advantages to producing a syngas rather than a fully combusted gas. For the same amount of waste, gasification will produce a smaller volume of gas since no fossil fuels are burned to generate heat and there is no need for excess oxygen as in most other thermal treatment. In addition, a smaller volume of gas costs less to clean. Also, a clean syngas can be turned into energy quite efficiently using either a turbine or an internal combustion engine. The syngas can also be converted to other gases or chemicals, such as methane (similar to natural gas), hydrogen or methanol.

The gas produced by thermal treatment of waste is typically subject to the local and national emissions regulations. The main components being regulated worldwide are acid gases, carbon monoxide, nitrogen oxides, particulates as well as dioxins and furans. In America and Europe, these standards are becoming increasingly strict. For example, in December 2005 the US EPA issued a new standard for the incineration of non hazardous solid waste (40 CFR Part 60) which reduces, for example, emission limits for SO_2 from 30 ppm to 3.1 ppm and NO_x limits from 500 ppm to 103 ppm.

4. APPLICATIONS OF PLASMA IN WASTE TREATMENT

Two examples of the use of plasma for waste treatment are rpesented below. The Plasma Arc Waste Destruction System's (PAWDS) goal is to destroy waste on board ships. The Plasma Resource Recovery System (PRRS) is used to recover energy and produce a vitrified rock from waste on land.

4.1 Plasma Arc Waste Destruction System (PAWDS)

Developed in collaboration with the U.S. NAVY, the Plasma Arc Waste Destruction System's (PAWDS) goal is to destroy waste while occupying the smallest amount of space possible. The result is a compact system, with no refractory material that occupies less than 65 m^2 (650 ft^2) on a single deck of a ship (Chronopoulos et al., 2005). The following picture is of the full size PAWDS system at Pyrogenesis in Montreal, Canada.

Figure 2 - PAWDS System

The PAWDS system can destroy all sorts of wastes such as paper, cardboard, plastic wood and textiles. A PAWDS system, installed onboard a Carnival Cruise Lines ship has destroyed well over 1,000,000 pounds (450,000 kg) since the fall of 2003. The PAWDS system can also destroy sludge oil at the rate of up to 200 liters per hour with up to 50% moisture content. Because the plasma torch is an independent source of heat, the performance of the system is not affected by the heating value of the oil and, as such, oil with high water content can be treated easily.

The PAWDS is a continuous process (Figure 3) in which the waste is first fed into a shredder where its size is reduced and then transported to a storage mixer using screw conveyors. A screw feeder is attached to the base of the storage mixer and is used to meter the waste into a blow-through airlock and then onwards to a mill. Air from a gasification blower is used to pneumatically convey the material to the mill. The mill pulverizes and dries the waste. The final product, leaving the mill, is a highly combustible and dry material that looks similar to lint from a household dryer. The milled waste "fuel" conveyed by air is then injected into a patented plasma-fired eductor (Nolting et al., 1997). In the eductor, this "fuel" is exposed to the high temperature of the plasma plume that results in rapid gasification of the solid waste into a synthesis gas. The resulting synthesis gas is then combusted with excess air in a patented (Tsantrizos et al, 2000), lightweight combustion chamber, resulting in a fully oxidized off-gas, comprised of carbon dioxide and water. Any inorganic substances in the waste are transformed into an inert ash.

Upon exiting the combustion chamber, the gases enter a quench, where water is sprayed to reduce the temperature of the gas to 80°C typically. Rapid cooling of the gas prevents any dioxin and furan formation, which typically occurs at temperatures between 200 and 500°C (Cernuschi et al., 2000; Lemieux et al., 2000). The cooled gases then enter a Venturi scrubber where particulates are removed from the gas stream by trapping and collecting them in the water stream. A cyclonic separator separates the water/ash stream from the gas stream prior to its discharge into the ship's stack. The ash/water stream inside the cyclonic separator is pumped through an in-line strainer or a deep bed filter to separate the inert ash fraction from the water. The strained water can be re-circulated to the quench spray nozzles to decrease the water consumption of the system aboard the ship.

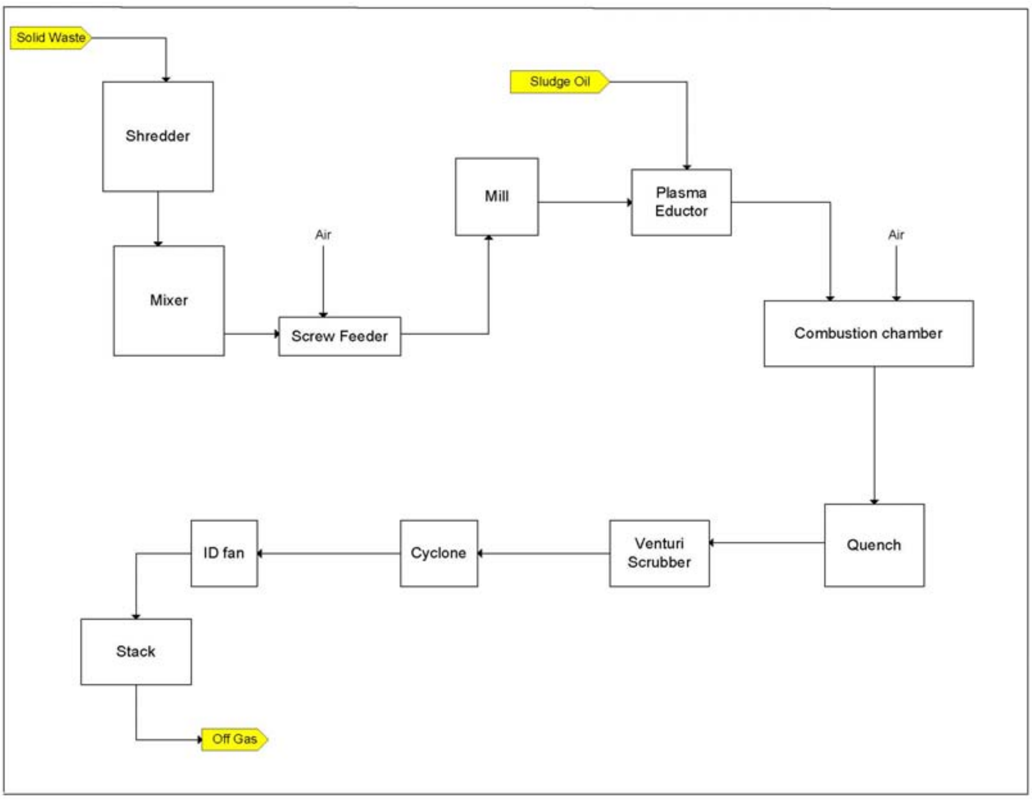

Figure 3 – PAWDS block diagram

4.2 Plasma Resource Recovery System (PRRS)

The PRRS technology combines plasma gasification and vitrification in a two step process (Carabin et al., 2004). The synthesis gas produced is cleaned and used for the production of electrical energy using gas engines or to produce various chemicals such as hydrogen or methane. Hot water and steam can also be produced by the engines as required and be used for various purposes such district heating or cogeneration of electricity and steam. Vitrification is the process of melting all the inorganic fraction of the waste to produce a metal alloy and an environmentally safe glassy slag that is suitable for use as a construction material. As a result, the system produces virtually no secondary wastes.

The vitrification occurs in an electric arc furnace, where the inorganic portion of the waste (metals, glass, dirt, etc.) is recovered into a molten metal phase and a molten inert slag phase. The temperature of molten slag and metal is maintained above 1,500°C. Also in the graphite arc furnace, the organic fraction of the waste is separated from the inorganic fraction. The organics are basically volatilized with the addition of small amounts of gasification air and converted into a crude synthesis gas.

The crude synthesis gas is then fed through a secondary gasifier, fired by a plasma torch, where the gas is reheated to 1,000°C by a combination of plasma and chemical energy. The patented secondary gasifier is essentially a plasma-driven eductor designed to mix the waste stream with air and moisture and expose the highly reactive mixture to the extreme temperatures of plasma. In the eductor, the contaminants in the crude syngas coming from the electric arc furnace such as tars and complex organic molecules are dissociated into their most simple form of CO and H_2.

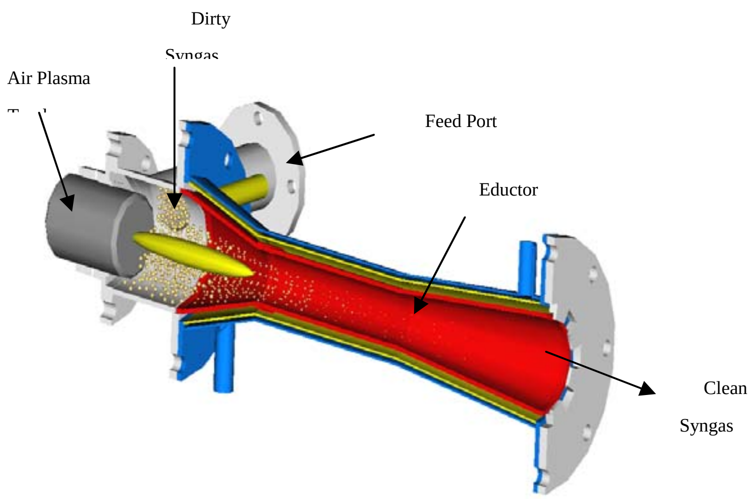

Figure 4 - Plasma driven eductor

The synthesis gas leaving the secondary gasification furnace contains a number of pollutants, including fine particles, volatile heavy metals, chlorides and sulfur. In the PRRS system, these pollutants are removed prior to combusting the synthesis gas in a gas engine. Furthermore, the humidity contained in the synthesis gas is also removed in order to improve its combustion properties. No further gas treatment is required at the engine outlet.

The syngas cleaning includes the following steps:

- Quench chamber, used for rapid gas cooling.

- Venturi scrubber, used for particulate removal.
- Packed Bed Scrubber, used for soluble acid gases removal (for example HCl).
- H_2S absorber, used for removal of H_2S.
- HEPA filter for fine particulate removal.
- Activated carbon bed filter for removal of heavy metals.
- Induced Draft Fan, for keeping the whole system under a negative pressure.

The clean synthesis gas can be used as fuel in a spark ignited internal combustion engine (gas engine), such as those produced by Jenbacher AG of Austria. Gas engines offer the advantage of high electrical production efficiency (35-40%), as compared to gas turbines (25%). Also, gas engine are suitable for producing electricity from low-BTU gas, such as the synthesis gas produced from the gasification of waste. (Herdin et al., 2003) have demonstrated the use of hydrogen containing low BTU gas in gas engines with the most extreme case at a LHV of 1.67 MJ/Nm^3. Herdin et al. have demonstrated that “excellent degrees of engine efficiency have also been attained using the H_2-rich gases, in part even up to 2 percentage points better than with the use of natural gas”, estimated at 45%. In addition, Herdin et al. have reported efficiencies above 40% when using syngas from a waste pyrolysis process. Other investigators (Min and Yoshikawa, 2004) have shown that the use of diesel type engines with low BTU gas could produce brake thermal efficiencies above 40%.

5. CONCLUSION

Plasma is well suited for use in the waste treatment industry. It requires only electricity and inert gases to operate as opposed to the fossil fuel used in incinerators. The very high temperatures allow for almost any type of waste to be destroyed, regardless of its own heating value. This makes plasma system very interesting for the treatment of hazardous waste, medical waste and incinerator ash.

Many novel applications of plasma in waste treatment are being explored around the world, with an increasing number of commercial and demonstration plant being in operation. The major obstacles to their widespread implementation are: the need for large capital investments, their unproven long term performance and public opinion regarding the thermal destruction of waste in general. As the average citizen realizes that landfilling the waste also has negative consequences such as odors and potential contamination of underground water, thermal treatment solutions such as plasma gasification are becoming more widely accepted.

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