# PLASMA WASTE TREATMENT: PROCESS DESIGN AND ENERGY OPTIMIZATION

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## EXTENDED ABSTRACT

Plasma treatment is a technologically advanced and environmentally friendly process of disposing waste materials and converting them to commercially usable by-products. Plasma treatment, technically known as gasification / vitrification, is a non-incineration thermal process that uses extremely high temperatures in an oxygen starved environment to completely decompose input waste material into very simple molecules. The by-products of the process are a combustible gas and an inert slag. Furthermore, it consistently exhibits much lower environmental levels for both air emissions and slag leachate toxicity than competing technologies, e.g. incineration.

A typical plasma treatment system consists of a feed preparation subsystem, a plasma furnace and a gas cleaning system. It is mentioned here that the amount of off-gas produced by the plasma furnace, is less than a half of the amount produced by a comparable capacity incinerator. Furthermore and most importantly, due to the high operating temperatures in plasma furnace and to the following rapid quenching with water, the formation of complex molecules, such as dioxins, is prevented.

The product gas of the process is actually a clean synthesis gas, composed primarily of hydrogen, carbon monoxide and nitrogen with smaller amounts of methane, acetylene and ethylene. Starting from this point, a proposal for an integrated process design of the plasma treatment is presented in this work. The main goal of the proposed process design is to optimize the overall efficiency of the system by recovering the maximum amount of energy, which is expected to be sufficient not only to satisfy the electricity requirements of the plant but also to be available for sale.

To this purpose, we present a preliminary energy / exergy analysis of the plasma waste treatment process along with the proposed energy recovery system. The importance of a cogeneration subsystem that will recover the energy of the produced synthesis gas, which results in steam and electricity production, is demonstrated. Preliminary results for the case of an organic waste indicate the production of 0.8 MW electricity (net value) and 0.9 MW of steam.

**Key words:** plasma, waste treatment, process design, energy recovery, exergy analysis.

## 1. INTRODUCTION

A factor common to all developed countries is the generation of excessive amounts of waste per capita. As societies develop, the amount of waste material generated has increased to a level that is unsustainable. This, together with the increasing awareness of the general public for the damage caused to the environment, explains why the need to plan for and implement sustainable and integrated strategies for handling and treating wastes has become a priority for many local authorities [1].

Plasma waste treatment, technically known as plasma gasification/vitrification technology, is a non-incineration thermal process that uses extremely high temperatures in an oxygen- starved environment to melt or vitrify the inorganic fraction of the waste and to gasify the organic fraction.

Although plasma as a method to generate heat is a well-demonstrated commercial technology at work around the world, its application to waste disposal is more limited. During the past twenty years, the use of plasma technology for waste disposal has undergone extensive research and small-scale development [2].

A plasma waste treatment system can treat a wide variety of industrial, household, hazardous and non-hazardous wastes through the use of plasma energy, which converts the organic fraction of waste into a clean fuel (synthesis gas) used to produce electricity and the inorganic fraction into stable, inert rocks that can be used as construction material. Moreover, the presented process offers significant advantages over alternative thermal waste treatment technologies, such as the permanent containment of all heavy metals and other hazardous materials, such as radioactive elements, within the vitrified slag; better energy recovery; and no production of ash, dioxins or other hazardous by-products [2,3,4].

## 2. PROCESS DESCRIPTION

### 2.1 Process design

The block diagram presented in Figure 1 includes the main sections of a plasma waste treatment plant. In more details, each section, apart from the energy recovery system, consists of the following compartments:

- Feed pre-treatment subsystem

The waste feed sub-system is used for the treatment of each type of waste in order to meet the inlet requirements of the plasma furnace. For example, for a waste material with high moisture content, a drier will be required. However, a typical feed system consists of a shredder for solid waste size reduction and a sealed hopper along with a screw feeder to drive the solid waste into the furnace.

- Plasma furnace

The plasma furnace is the central component of the system where gasification/vitrification are taking place. Two graphite electrodes, as a part of two transferred arc torches, extend into the plasma furnace. An electric current is passed through the electrodes and an electric arc is generated between the tip of the electrodes and the conducting receiver, i.e., the slag in the furnace bottom. The gas introduced between the electrode and the slag that becomes plasma can be oxygen, helium or other, but use of air is very common due to its low cost.

- Gas cleaning subsystem

The gas cleaning subsystem has to achieve the elimination of acid gases (HCl, $SO_x$) suspended particulates, heavy metals, and moisture from the synthesis gas prior to energy recovery system. To that purpose, a typical gas cleaning system consists of:

a) A water quench for the immediate cooling of the hot and dirty synthesis gas to avoid the formation of complex molecules like dioxins.
b) A venturi scrubber to remove particulates
c) A packed bed tower scrubber using caustic solution to neutralize the acid gases. Moreover, by sub-cooling the scrubbing solution, the moisture in the gas is removed and condensed in the solution, and
d) Filters for the entrapment of heavy metals and other fine particulates.

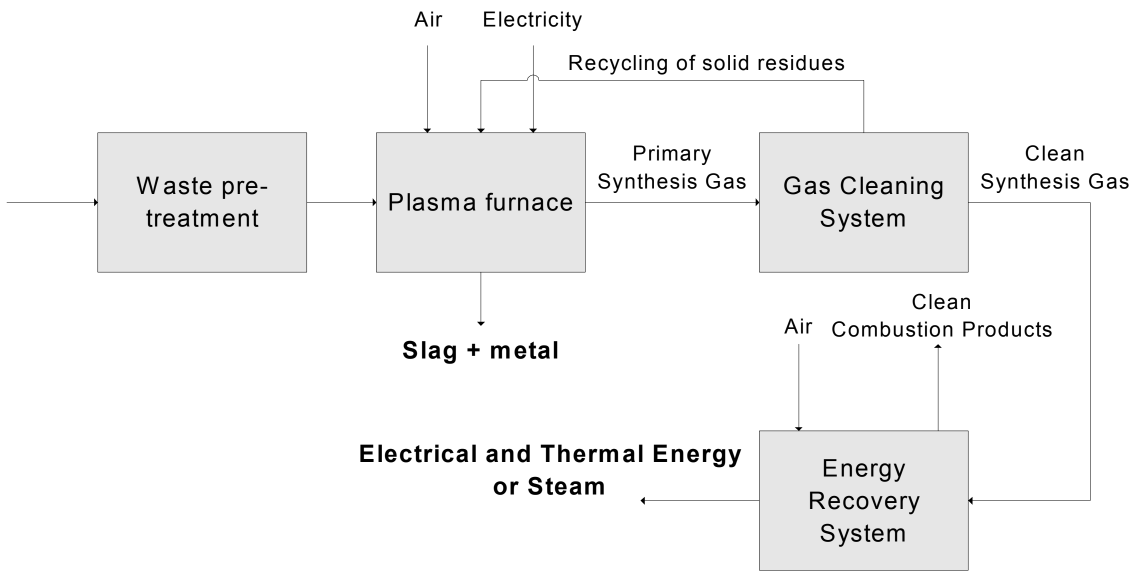


**Figure 1:** Block diagram of plasma waste treatment process

## 2.2 Energy recovery system

The energy recovery system can be based on a steam cycle, gas turbine cycle or a gas engine. Depending on the quality of the produced synthesis gas, the best option can be one of the above energy recovery scenarios.

In this work, the option of a cogeneration system, based on a gas turbine combined cycle, is selected as the one that allows electrical efficiency of >40% to be achieved [1,5]. This electrical efficiency is the highest among the other alternative schemes, although the fact that this kind of plant has the need for a good cleanup system that is not essential for other cases, e.g. steam cycle. In addition, studies on the selected cogeneration system confirm its high efficiency, either by reporting simulation results [6,7], or by its implementation in commercial scale systems, e.g. Termiska Processer ARBE project at Eggborough, in United Kingdom [5] or the Solena Group system in U.S.A.[2].

The proposed energy recovery system (Figure 2) consists of an air and gas compressor, a combustion chamber, a gas turbine, and a Heat-Recovery Steam Generator (HRSG), where the hot combustion gases are used for the production of the high-pressure steam. The produced steam can be used either directly, for example for drying of the waste material, or for production of an additional amount of electrical energy.

## 3. GASIFICATION EQUILIBRIUM MODELING

The central part of the plasma waste treatment process is the plasma furnace. Inside the plasma furnace, various chemical reactions take place that are difficult to be reproduced by a simple equilibrium model. Nevertheless, models based on thermodynamic equilibrium have been used widely and they are convenient enough for process studies on the influence of the most important waste and process parameters [8,9].

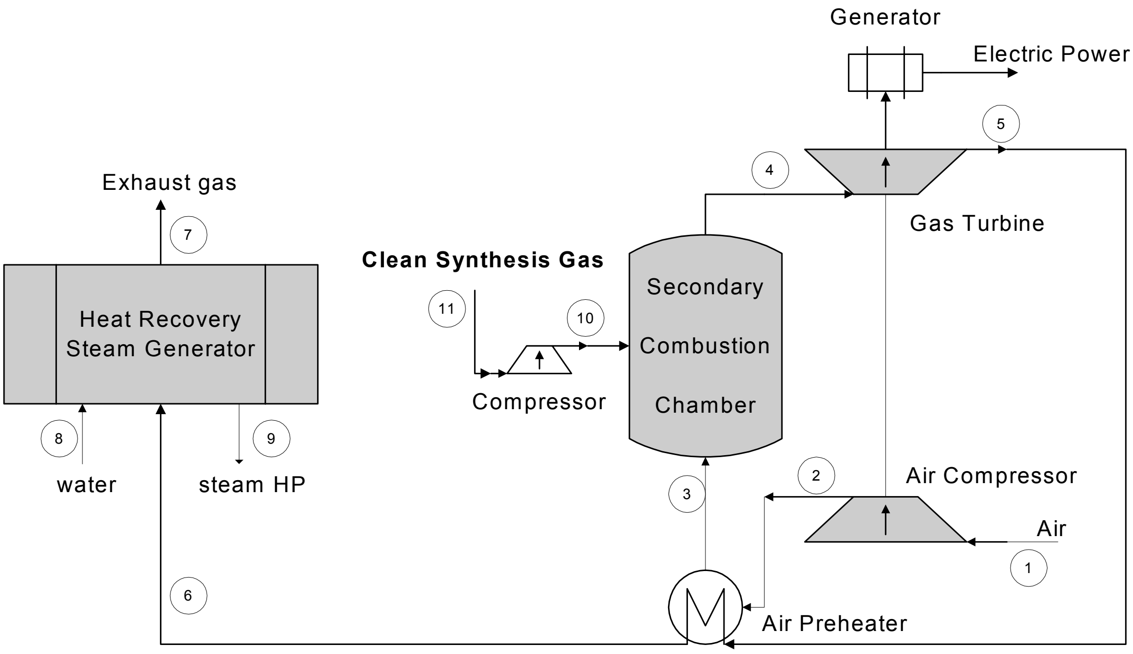


**Figure 2:** Energy recovery system – Cogeneration of steam and power

In present analysis, two equilibrium reactions are selected after a common combination procedure [10] as the main and independent gasification reactions of the equilibrium model, namely methane decomposition and water gas shift reaction, as shown below:

$CH_4 + H_2O = CO + 3H_2$ (Methane decomposition)

$CO + H_2O = CO_2 + H_2$ (Water gas shift reaction)

The equilibrium is calculated considering the components $CH_4$, CO, $CO_2$, $H_2$, and $H_2O$. System analyses show that simultaneous equilibrium is described by three partial mass balances (for C, H and O) and one heat balance, assuming that the gasification process is adiabatic. The specific heats and enthalpy changes of the gas products are expressed as a function of the gasification temperature, as well as the equilibrium constants of the chemical reactions [11].

## 4. ENERGY – EXERGY ANALYSIS

A detailed thermodynamic model is used for the selected cogeneration system in order to calculate, through the consideration of the energy balance equations [12] in each section of the system, the generated net power as a function of the synthesis gas composition and mass rate.

Exergy analysis (availability analysis, second thermodynamic law concept) is applied to the plasma treatment system by calculating the exergy input and output rates for the main sections of the process, i.e. the plasma treatment and energy recovery subsystems.

In addition, exergy analysis is applied to the selected cogeneration system in order to identify any component with low efficiency or the component that is primarily responsible for the low overall efficiency. Exergy analysis includes the calculation of the exergy rate (physical and chemical) of each stream and the calculation of exergy loss rates calculated in each compartment of the system.

For the calculation of the physical exergy of each stream *i* the following equation is used:
$E_i^{PH} = m_i \cdot [h_i - h_0 - T_0(s_i - s_0)]$,
and for the calculation of the chemical exergy of each stream the required standard chemical exergies of each substance are collected from the literature [12]. For the case of the feed waste material, its chemical exergy is estimated by the equation presented in Zhong et al. [13]

## 5. A CASE STUDY: A WOOD WASTE

### 5.1. Composition of synthesis gas

In this work, the solid wood waste (70 tons/day) from a wood furniture manufactory is studied as the input of the plasma waste treatment plant. An ultimate chemical analysis was conducted for the determination of the elemental composition of the wood material as well as the experimental determination of the heating value of the wood material, data that are required in the input of the gasification equilibrium model and the energy model.

The predicted synthesis gas composition is presented in Table 1, for the case of wood waste material at gasification temperature of 1073K and moisture content of 7.2%. The global gasification reaction, which reflects only the overall mass balance and is formed by the use of the predicted values of the selected parameters, is as following:
$CH_{1.49}O_{0.66}$ +*0.103*$H_2O$ +*0.347*$O_2$ +*1.406*$N_2$ =*0.557*$H_2$ +*0.609*CO +*0.336*$CO_2$ +*0.181*$H_2O$ +*0.055*$CH_4$+*1.406*$N_2$

**Table 1.** Equilibrium model results for wood material at 3.75% (v/v) moisture content and gasification temperature of 1073K.

| Components (% v/v) | Gas composition | Dry basis | Oxygen added | Moisture feed content |
|---|---|---|---|---|
| Hydrogen | 17.72 | 18.80 | 12.6 v/v | 3.75 v/v |
| Carbon monoxide | 19.38 | 20.56 | Wet basis | |
| Carbon dioxide | 10.69 | 11.34 | | |
| Water | 5.75 | - | | |
| Methane | 1.75 | 1.86 | | |
| Nitrogen | 44.72 | 47.45 | | |
| Sum | 100.00 | 100.00 | | |

The gasification equilibrium results are in reasonable agreement with the reported results in the literature [9,13] for the case of wood waste material and similar values for the gasification parameters.

### 5.2. Electrical energy and steam production calculation

The cogeneration model results are presented in Table 2. The products of the process are electrical energy equal to 1.8MW and high-pressure steam with a mass rate of 1 Kg/s and pressure of 20 bars. Preliminary calculations by a steam turbine calculator [15] show that 0.5 MW of electrical energy can be produced by the use of the high-pressure steam.

The calculated electrical efficiency of the system is equal to 1.8MW / 4.5MW =0.41, which can be characterized as a high electrical efficiency value. It is mentioned here that the electrical energy consumption of the integrated plasma waste treatment plant is estimated to be near 1 MW. Consequently, a significant amount of power is generated that can be available for sale and contributes to the reduction of the operational cost of the process.

**Table 2.** Obtained results from the application of the cogeneration model.

| Input waste | Flow rate | Fuel gas | Net Power output | Steam |
|---|---|---|---|---|
| Mass (wet) Wood waste | 0.81 kg/s | 0.266 kg ($CO + H_2$)/s | 1.8 MW | 1.00 kg/s |
| Moisture | 0.06 kg/s | 5.56 kg air/s | | 20 bars |
| Oxygen | 0.33 kg/s | (4.5MW) | | (~0.5 MW) |

### 5.3. Exergy analysis results

The exergy input and output rates for the main sections of the process are shown in Table 3. It appears that the plasma treatment section has a high exergetic efficiency factor (16.3/18.3=0.89) as the chemical exergy of the waste material is simply converted to another valuable form of chemical exergy, that of synthesis gas.

**Table 3.** Exergy data for the plasma waste treatment process.

| | Input | Output | | | |
|---|---|---|---|---|---|
| Feed | Exergy | Plasma treatment - Exergy | | Cogeneration - Exergy | |
| Waste | 17.3 MW | Synthesis gas | 16.3 MW | Electricity | 1.8 MW |
| Moisture | 0.0 MW | Slag + loss | 2.0 MW | Steam | 0.9 MW |
| Oxygen | 0.0 MW | | | | |
| Electricity | 1.0 MW | | | | |

On the other hand, the exergetic efficiency for the cogeneration system is calculated as the percentage of the exergy supplied to the system that is recovered in the product of the system. Identifying the product of the cogeneration system as the sum of the net power generated and the net increase of the exergy of the feed water, it results in:

$$\varepsilon = \frac{W_{net} + (E_9 - E_8)}{E_{11} + E_1} = 0.165$$ , or else 16.5%.

The exergy loss data of Table 4 clearly identify the combustion chamber as the major site of thermodynamic inefficiency, with the chemical reaction to be the principal irreversibility and the main cause of the destruction of the synthesis gas' chemical exergy.

Regarding the overall plant efficiency (2.7 / 18.3 = 0.148), the low percent of 14.8% is the result of the high chemical exergy of the waste material and it does not represent the real efficiency of the overall plant. Combustion is intrinsically a very significant source of irreversibility, and a dramatic reduction in its effect on exergy loss by conventional means, e.g. preheating of the air or reducing the air-fuel ratio, cannot be expected [12]. In fact, the only significant way to preserve the chemical exergy present in the waste material and the produced synthesis gas is to transform it to another chemical one, for example methanol [16].

**Table 4.** Exergy loss data for the cogeneration system.

| | Exergy rates (MW) | | Exergy loss (MW) | | Exergetic Efficiency |
|---|---|---|---|---|---|
| Component | Input | Output | Rate (MW) | Percent* | % |
| Gas compressor | 16.473 | 16.368 | 0.105 | 0.779 | 35.1 |
| Combustion chamber | 18.825 | 6.436 | 12.389 | 92.140 | 34.2 |
| Heat Recovery Steam Generator | 1.573 | 1.082 | 0.491 | 3.651 | 64.9 |
| Gas Turbine | 6.436 | 6.252 | 0.184 | 1.367 | 95.3 |
| Air preheater | 4.174 | 4.022 | 0.152 | 1.133 | 78.3 |
| Air compressor | 1.759 | 1.634 | 0.125 | 0.931 | 92.9 |
| Overall cogeneration plant | 49.239 | 35.794 | 13.446 | 100.000 | 16.5 |

* of total exergy loss

Nevertheless, significant increase of the system power generation, and as a result of the overall efficiency, can be achieved by improving the synthesis gas quality. This can be done by adjusting the amount of air or moisture added during gasification process and, to a larger extend, by the use of a secondary plasma gasifier [17] for the complete transformation of the organic fraction of the waste into carbon monoxide and hydrogen. By this way, the mass rate of the fuel synthesis gas will be increased (calculated as the sum of the CO and $H_2$ mass rates) and, thus, the amount of electrical energy generated.

## 6. CONCLUSIONS

Application of plasma waste treatment technology results in the conversion of all organic waste into synthesis gas, which can be used as fuel, and all inorganic waste into vitrified slag that can be used safely as construction material. The produced synthesis gas can be used efficiently for energy recovery purposes with a view not only to satisfy the power requirements of the plasma waste treatment system but also to generate an excessive amount of electrical energy, available for sale.

In this work, for the case of an organic waste material, and after the prediction of the composition of the produced synthesis gas from the plasma furnace, the energy performance of the integrated plasma waste treatment system was evaluated and the obtained results show that the process is suitable for power generation from waste material. Although the exerggy efficiency of the plasma treatment section is high (89%) and the energy efficiency of the selected energy recovery system is also high (41%), the exergy efficiency of the overall process is low (17%). This is due to the exergy loss – chemical exergy to heat – in the combustion chamber. Furthermore, it is anticipated that adjustment of the operational parameters, e.g. air rate and feed moisture content in the plasma furnace and use of a secondary gasifier for the complete conversion of the organic waste into synthesis gas, can improve the overall performance of the system and increase the power production.

In conclusion, the proposed process, not only achieves elimination of the waste but also produces - in the case of the wood waste - 0.8 MW of electricity and 0.9 MW of steam.


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