PLASMA GASIFICATION OF SEWAGE SLUDGE: EQUILIBRIUM MODELING AND EXERGY ANALYSIS

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SUMMARY
Plasma gasification, a solid waste thermal treatment method, appears to be an effective way for the treatment of sewage sludge produced at central wastewater treatment plant in Athens, Greece. In order to show the effectiveness of such a treatment alternative, an equilibrium gasification model was developed for the prediction of the composition of the synthesis gas produced after the treatment of sewage sludge inside the plasma furnace. The exergy of the synthesis gas is then calculated and compared to the electricity consumption of the furnace. Obtained results show that the process not only is self-supporting, but a significant amount of energy is available for other applications.

INTRODUCTION
During the wastewater treatment process a rest product, described as sewage sludge, is formed with a low dry solids content. The ways of disposing this waste have varied with the development of civilization and technology. Today, dumping of sludge on land or into the sea, the most primitive sludge treatment, is forbidden in many countries. As still increasing amounts of sludge are produced, more advanced methods of sludge treatment have to be developed.

Furthermore, there is a growing change in the perception of sludge from an unwanted waste to a beneficial resource and it is important to develop a suitable technology or use an existing one in order to reduce the environmental problem and costs of sludge treatment. Plasma gasification technology can be applied to convert the sewage sludge into a usable energy and to reduce the waste volume. Additionally, it eliminates toxic organic compounds and fixes the heavy metals in the inert slag while it produces synthesis gas that can be utilized in an energy and heat recovery system for electricity production.

In this case study, sewage sludge from the main wastewater treatment plant of Athens at Psittalia island, is considered to be the waste material to be subjected to plasma gasification treatment. At Psittalia, after primary treatment of municipal wastewater along with industrial wastes, ~250 tones per day of sludge are produced [1].

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PROCESS DESCRIPTION

Plasma gasification is a technologically advanced and environmentally friendly process of disposing waste materials and converting them to commercially usable by-products. It 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 [2]. 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 (Figure 1) consists of a feed preparation subsystem, a plasma furnace, a gas cleaning system and a secondary combustion chamber for the complete transformation of organic combustible materials into benign gases (primarily nitrogen, water vapour and carbon dioxide). The product gas of the gasification reactions inside the plasma furnace is actually, after the gas cleaning procedure, a clean synthesis gas composed primarily of hydrogen, carbon monoxide and nitrogen with smaller amounts of methane, acetylene and ethylene [3]. The main goal of the proposed process design for the treatment of sewage sludge is to improve the overall efficiency of the system by recovering the maximum amount of energy, which appears to be sufficient not only to satisfy the thermal and electricity requirements of the plant but also to be available for sale.

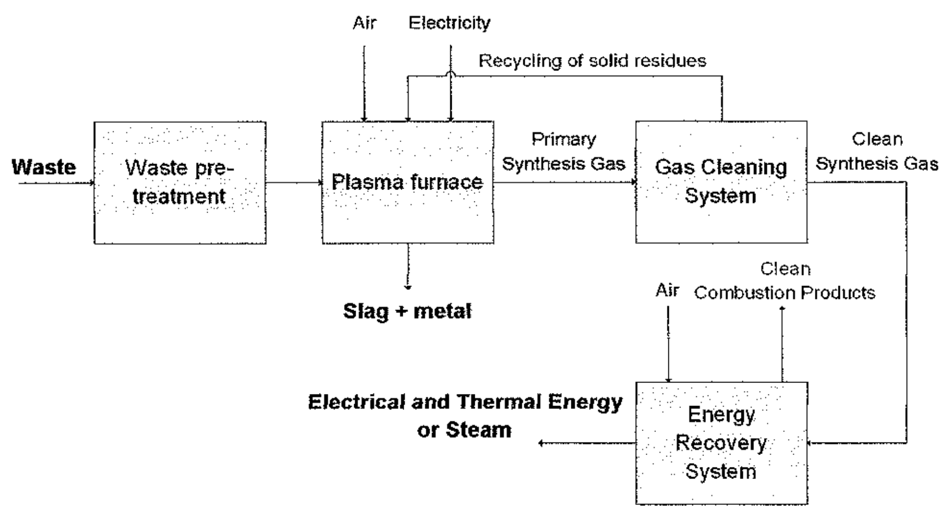

Figure 1. Diagram of a typical plasma waste treatment process

Equilibrium gasification 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 [4],[5].

In the present analysis, two equilibrium reactions are selected after a common combination procedure [6] 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 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 [7].

Exergy calculations

The chemical exergy of the gas mixture is determined by the composition and concentration of components in the mixture [8]:

$$\varepsilon_{o,m} = \sum_i x_i \varepsilon_{0,i} + RT_0 \sum_i x_i \ln x_i$$

where x_i are the molar fraction of each component, $\varepsilon_{0,i}$ is the standard chemical exergy (Kj/kmol) of each component, e.g. ε_{H2}= 235249kJ/kmol and ε_{CO}=269412kJ/kmol, and $\varepsilon_{0,m}$ is the chemical exergy of mixture (kJ/kmol).

RESULTS AND DISCUSSION

An ultimate chemical analysis was conducted for the determination of the elemental composition of the sewage sludge before the anaerobic digestion as well as the experimental determination of its heating value, data that are required in the input of the gasification equilibrium model (Table 1). Moreover, the feed moisture content is assumed to be 30% w/w dry basis after drying as the sewage sludge has high initial moisture content (70% after mechanical dewatering) and with a view to avoid further drying of the sludge. Furthermore, this moisture content is in the acceptable range of the moisture content value for the input of the plasma furnace. A typical gas composition obtained from the model is given in Table 1 and it corresponds to 0.05moles O_2 /100moles of dry waste material leads to a gasification temperature of 1550°C.

Table 1. Ultimate analysis of sewage sludge and equilibrium gasification model results

Sewage sludge		Synthesis gas			
Element	(% w/w)	Components	Gas composition (% v/v)	Dry basis	Oxygen added
C	37.6	H_2	38.56	44.51	0.05 mol/mol dry waste
H	5.5	CO	18.91	21.83	
O	54.3	CO_2	17.67	20.40	
N	2.6	H_2O	13.37		Moisture feed content 30% w/w
S	0.0	CH_4	1.96	2.26	
Ash	31.4	N_2	9.53	11.00	
Heating value 16600 KJ/kg		Sum	100.00	100.00	

The global gasification reaction, which reflects the overall mass balance and is formed by the use of the predicted values of the selected parameters, is as following:

$$CH_{1.76}O_{1.08} + 0.57H_2O + 0.05O_2 + 0.25N_2 = H_2 + 0.49CO + 0.46CO_2 + 0.35H_2O + 0.05CH_4 + 0.25N_2$$

The chemical exergy of the produced synthesis gas is equal to 9.5 MW. Considering the fact that the amount of electricity added in the plasma furnace is estimated to be 1.5 MW and the required energy for the drying of the sludge is estimated to be 4.0 MW, the net exergy production of the plasma treatment process is 4.0 MW. This exergy value shows that the process has the potential to be self-supporting and it can be used for energy production, too.

For the optimization of the process a preliminary parametric analysis was conducted and it showed that increase of the moisture content has a negative effect on the chemical exergy of the produced gas and increase of the temperature upgrade the quality of the produced gas as well as its exergy content. In addition, increase of oxygen amount results in decrease of the chemical exergy of the synthesis gas. Further analysis need to be done with a view to fully optimize the process and to produce a good quality synthesis gas by using a low amount of electricity.

CONCLUSION

Plasma gasification appears to be one of the most promising alternatives for the treatment of sewage sludge. Equilibrium gasification model results show that a good quality synthesis gas is produced that can be used effectively in an energy recovery system to produce electrical energy not only to satisfy the requirements of the plasma furnace but also to be available for sale, as preliminary exergy calculations indicate so. However, future work must include the further optimization of the process with respect to the selected gasification parameters (oxygen amount, moisture content, electricity, gasification temperature).

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